Using eDNA to detect
ELUSIVE ANIMALS

The complex math of
BEACH PEBBLES

Policy and ecology clash in
WILDFIRE CONTROL

AMERICAN
Scientist

May–June 2023

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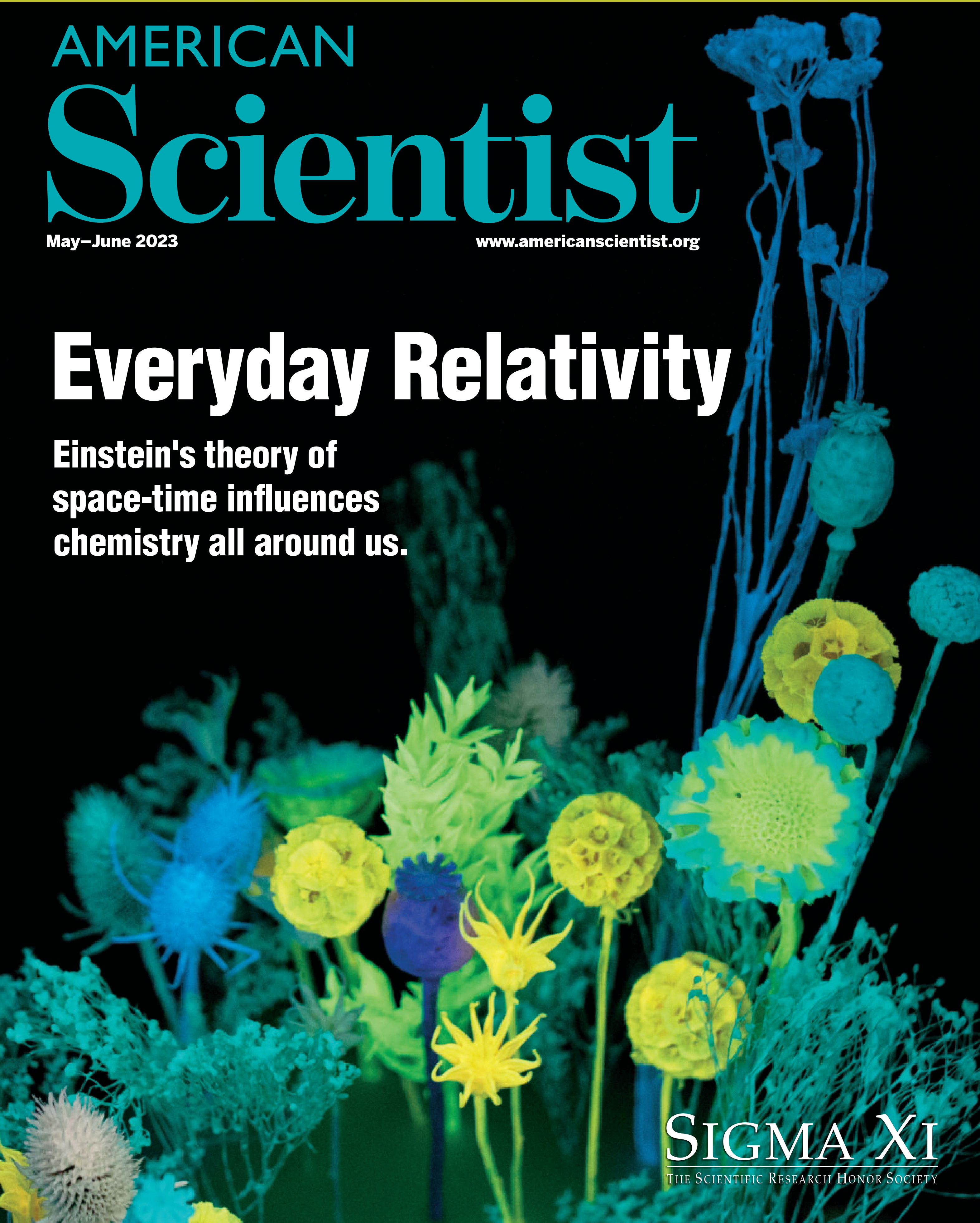
Everyday Relativity

Einstein's theory of space-time influences chemistry all around us.



SIGMA XI
THE SCIENTIFIC RESEARCH HONOR SOCIETY

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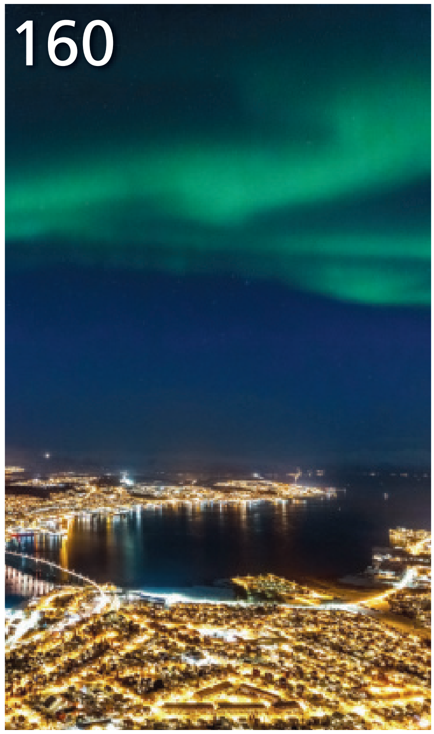
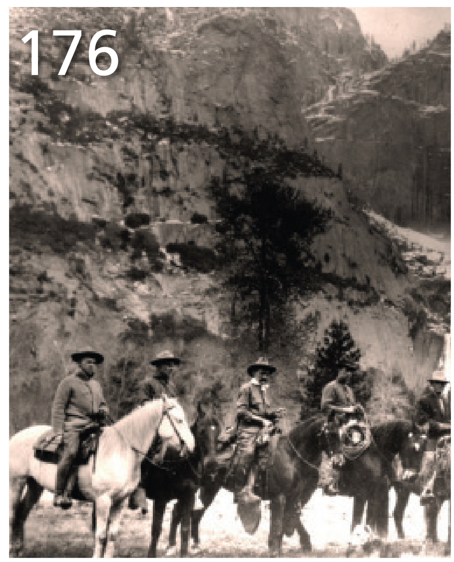
Departments

Scientists' Nightstand

From Sigma Xi

Feature Articles





The Cover

Phosphorescent pigments imbue the glow-in-the-dark floral artwork titled Moonbeam Flora, *created by science artist Tyler Thrasher, and are a good example of Einstein's theory of relativity in action in the world of molecules and materials. Relativity, through an effect known as* spin–orbit coupling, *allows an excited electron to return to its ground-state home orbital by a slower, circuitous route, while emitting a photon—a process referred to as* phosphorescence. *Phosphorescent materials hold great promise as medical imaging agents, such as for imaging of oxygen in tumors. And phosphorescence is just one of a myriad of ways in which relativity permeates molecular phenomena. In "Relativity and the World of Molecules" (pages 160–167), Abhik Ghosh and Kenneth Ruud discuss how relativity is omnipresent in chemistry, especially with heavy elements in the lower part of the periodic table. (Artwork by Tyler Thrasher, www.tylerthrasherart.com)*

Inspiring Environments

Seeing the northern lights is breathtaking, and those viewing them may wonder how they come about, but it's fairly safe to say that few observers are thinking about relativity when considering the origins of these auroras. Indeed, relativistic effects aren't just confined to physics, and as Abhik Ghosh and Kenneth Ruud explain in "Relativity and the World of Molecules" (pages 160–167), relativity is involved not only in auroras but also in phosphorescence, the color of gold, the state of mercury, and many other chemical phenomena. Auroras are one way that relativity makes the world more beautiful, say Ghosh and Ruud, and as professors at the world's northernmost university, UiT–The Arctic University of Norway in Tromsø, they are able to observe these lights, and draw inspiration from them, frequently.

A different natural phenomenon offering beauty and serenity is the focus of another feature in this issue, "The Mathematics of Beach Pebbles" (pages 168–175), by Theodore P. Hill and Kent E. Morrison. They evaluate the challenges with modeling how stones tossed about in waves tend to become oval in shape rather than spherical. The history of this inquiry is a fascinating lesson about ensuring that a model includes all relevant data, but the work also has important implications for understanding Martian geology, erosion, and the strength of materials such as concrete.

Treatment of the world around us is a central point in "Pyrocene Park" (pages 176–182) by Stephen J. Pyne. Past fire prevention policies, says Pyne, have paradoxically endangered the environment in Yosemite National Park, allowing it to become overgrown. Although prescribed burns were returned to the park in the 1970s, balancing the practice with more frequent, dangerous wildfires has proved to be complicated. But the situation as it stands threatens a grove of ancient sequoias that require protection.

In Perspective, the environment itself is shown to be a source of genetic data about its inhabitants. Asia Murphy, in "Wildlife Surveys Out of Thin Air" (pages 152–155), talks about new methods of obtaining DNA from the environment: Advances in sampling and analysis now allow for extraction of an organism's genetic material from the air, the water, blood samples from parasites, and other substrates. These techniques can help characterize what organisms have been in an existing ecosystem. Researchers are also developing ways to quickly capture and analyze RNA in the environment.

In this issue's Policy column, Christian H. Ross and Samantha Jo Fried look at the environment from multiple perspectives. In "Why STEM Education—and Democracy—Need Civic Science" (pages 156–159), the authors argue that STEM students need training on how to engage with diverse communities while putting science in a context that will help to solve societal problems. Some of these civic science training programs involve such forms of environmental service as removing introduced plant species or testing water for microplastics.

This issue's Engineering column also considers location. In "Museums of Bridges" (pages 148–151), Henry Petroski looks at structures in rural areas and discusses the different ways that engineers and architects consider how to blend their creations with a natural setting to enhance the experiences of visitors.

How do you draw inspiration from the world around you, either from the natural environment or the setting in which you find yourself? Consider yourself invited to let us know by either sending us a message through our website or joining us on social media to share your thoughts.

—Fenella Saunders (@FenellaSaunders)

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American Scientist gratefully acknowledges support for "Engineering" through the Leroy Record Fund.

Building Artificial Leaves for Renewable Energy Storage
Inspiration from photosynthesis could lead to technology that converts solar power directly to liquid fuels. Jillian Dempsey, deputy director of the Center for Hybrid Approaches in Solar Energy to Liquid Fuels (CHASE) at the University of North Carolina at Chapel Hill, discusses how this technology could fill in the gap in renewable energy sources that will help to limit global temperature rise to below 2 degrees Celsius.
www.amsci.org/node/5059

Advances in Personalized Medicine
Researchers and clinicians have many molecular tools for assessing a patient's individual response to a drug, but pharmaceutical companies still formulate medicines for the "average" person. Raeanne Geffert, a pharmacology PhD student at the University of North Carolina at Chapel Hill, asks, What is delaying the implementation of personalized medicine?
www.amsci.org/node/5061

Arsenic and PFAS found in Guatemala City's Public Water
Residents of Guatemala's capital collaborated with public health scientists to detect heavy metals and forever chemicals in their tap water. Jennifer Hoponick Redmon, director of environmental health and water quality at the Research Triangle Institute, led the project, which was the first of its kind in Central America.
www.amsci.org/node/5058

Modeling Digestive Diseases
Stomach cramps from exercise may seem like a minor inconvenience, but they can lead to more significant damage. Liara Gonzalez, assistant professor in the College of Veterinary Medicine at North Carolina State University, describes her research into how this injury occurs and how reserve intestinal stem cells may help the organ heal.
www.amsci.org/node/5056

Antimicrobial Resistance Is Just the Tip of the Iceberg
Drug-defying bugs create new challenges for global health. Siddhartha "Sid" Thakur, director of the Global Health Initiative at North Carolina State University, discusses the multidisciplinary and global approach he uses to understand and monitor emerging drug-resistant microbes.
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Physicians Need Caregiving Support Policies

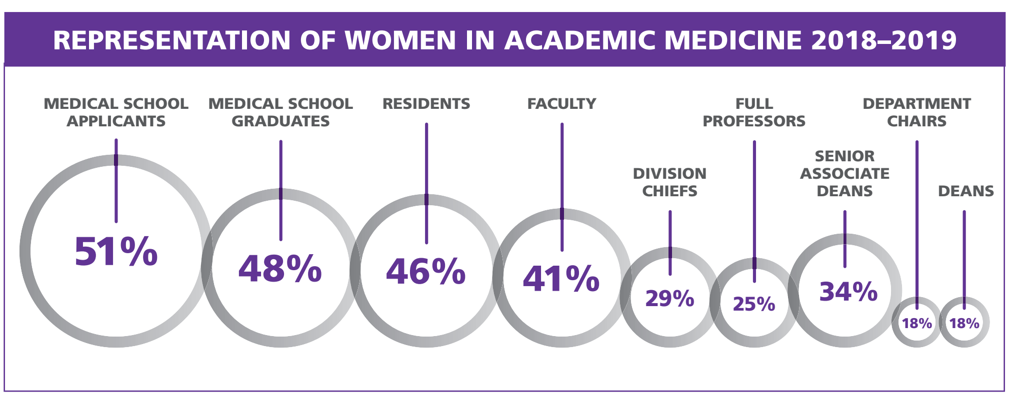
The collision of the Great Resignation and long-standing gender inequities in medicine is heightening calls for improved family leave policies at American health care institutions.

Even before the COVID-19 pandemic hit in 2020, rates of promotion and retention for women physicians were known to fall far short of gender parity. Although just over 50 percent of medical students are women, only 37 percent of practicing doctors are women. A 2020 report by the Association of American Medical Colleges shows that representation of women in academic medicine declines as one climbs the promotional ladder (*see the figure on the right*). One 2019 study showed that nearly 40 percent of women physicians left the career or cut back their hours within six years of finishing their residencies. Moreover, a 2022 *JAMA Network Open* study showed that little progress had been made between 1990 and 2019 to increase the number of women faculty of color in academic medicine, despite some progress among white women. Research has repeatedly shown that women in medicine report higher rates of burnout and depression than men do, and they cite home responsibilities as primary reasons for leaving their jobs, cutting back hours, or missing out on promotions.

Managing the stressors associated with the pandemic—including caregiving needs at home and strained health care and childcare systems—disproportionately fell to women, especially those of color. Comprehensive data are not yet available, but a December 2021 survey of 9,266 physicians at 124 U.S. institutions found that 1 in 5 physicians planned to leave their practices within two years. Given that women are already more likely to leave the field, this information points to a looming postpandemic spike in attrition among women physicians. "We're facing an existential threat in academic medicine," says Christina Mangurian, a psychiatrist, an expert on caregiving support policies, and the vice dean for faculty and academic affairs at the University of California, San Francisco, School of Medicine. "We could lose a ton of women right now."

Supportive family leave and childcare policies are an effective way for institutions to make a big difference in retention. The amount of support a physician has varies substantially by state and institution. "Evidence from the business world shows that generous parental leave and caregiving policies lead to workers who feel more connected to the organization and are less likely to leave," says Neda Laiteerapong, an associate professor of medicine at the University of Chicago. "But academic medical schools are not at the forefront on this issue." Such policies have known and established benefits. "Limited paid parental leave policies have been shown to increase rates of burnout, increase rates of mental health problems, and lower rates of breastfeeding," Laiteerapong says. Faced with a workplace that asks them to take on more work, but advances them less, many women decide to leave.

When women physicians leave their careers, all sorts of problems compound: Many health care institutions cannot afford to lose part of their



Cartoon by Hannah Wirenfeldt Moore/Northeastern University; Courtesy of Association of American Medical Colleges

Even before the COVID-19 pandemic, rates of promotion and retention for women physicians were low in academic medicine (as well as corporate health care). Add in the stressors of the pandemic, and a spike in attrition appears to be imminent. Big changes in policies supporting childbearing and caregiving are needed to curb the loss of women from these careers.

labor pool, and the remaining workforces do not reflect the populations that they serve. As a physician shortage looms, calls for implementing policies that support equity at the institutional, state, and national levels have taken on a sense of urgency. (*See "Balancing Home and School," November–December 2022.*)

Despite the clear need—and despite abundant evidence of the benefits of paid leave for workers and patients alike—research shows that medical employers generally do not have adequate family leave policies. A study published in January in *JAMA Network Open* and led by Laiteerapong found that only 15 percent of medical schools offered their faculty 12 weeks of paid parental leave. Forty percent had no adoption paid leave policy at all, and 75 percent had no foster paid leave policy. Due to the early-career demands of the profession, many physicians need policies that support the unique challenges of in vitro fertilization, adoption, or foster parenting. The study also showed that highly ranked and well-funded institutions tend to offer the most supportive policies. "Very few physicians practice at the top institutions," Laiteerapong says, pointing out that most physicians are left out of the group with flagship policies.

"The majority of workers in this country are family caregivers at some point in their career," says Jessica Lee, director of the Pregnant Scholar Initiative at the Center for WorkLife Law, based at the University of California, San Francisco (UCSF). "Yet the STEM education career pathway was designed for folks who weren't managing family care." Even when policies appear to be in place, the details and wording can block access to them. "[STEM professionals] keep hitting a brick wall of bureaucracy," Lee says. "It's infuriating and heartbreaking to see these generations of brilliant minds thrown off track, completely needlessly."

About 16 percent of physician mothers in the United States are informal caregivers for parents or children, according to a 2019 study led by Mangurian. She has assessed policies that support caregivers in medicine at all career levels. The focus for supporting caregivers has largely been on new parents, but Mangurian found that more of the faculty doing informal caregiving at her institution were caring for their elderly parents than young children, pointing to the need for policies that take into account all forms of caregiving.

Changes are happening at the national, state, and institutional level, although most existing policies still fall short of the support caregivers need. In March, the U.S. Commerce Department announced that tech companies seeking federal funding through the CHIPS and Science Act, a law passed last year that provides about $280 billion of funding for domestic research and manufacturing of semiconductors, will be required to provide childcare for their workers. An increasing number of states are creating parental and family leave standards that are more generous than those set at the national level by the U.S. Family and Medical Leave Act, which requires employers of a certain size to offer 12 weeks of unpaid leave—one of the least generous parental leave policies among developed countries. In 2022, Maryland, Virginia, and Delaware all updated their parental and family leave policies, with Maryland and Delaware requiring 12 weeks of paid leave. At the institutional level, medical professionals are seeing more policies that recognize the importance of supporting employees that have caregiving responsibilities at home.

Only 15 percent of medical schools offered their faculty 12 weeks of paid parental leave.

Even when leave and childcare policies are in place, there are barriers to accessing them. For example, in many cases in which daycare is available through an employer, waitlists are often so long that in order to guarantee a spot, parents need to get on the list before they even know whether they will have a baby to enroll. Lee points out that having a family leave or childcare policy on paper doesn't always mean every employee can access that support.

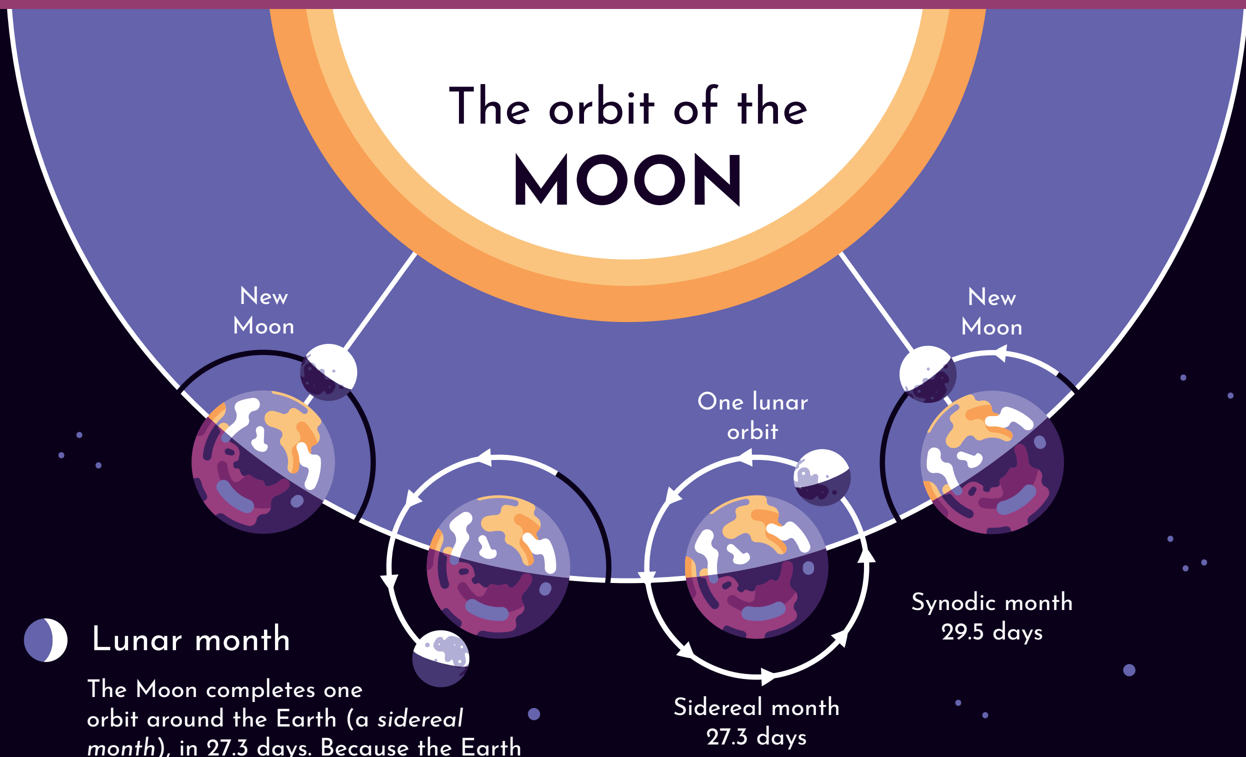
The problem pervades all levels of the medical profession. There is no standardized, standalone parental leave policy for medical students. For residents, the Accreditation Council for Graduate Medical Education (ACGME) last year raised their standard to six weeks of paid leave, which is progress but still far shorter than the 12 weeks recommended by the American Academy of Pediatrics or the paid leave offered in other developed countries.

Some specializations are shockingly out of step with contemporary workplace culture. Lee coauthored a study published in the *Journal of the American College of Cardiology* last year that surveyed 323 women in the profession about their experiences with childbearing and parental leave. She and her coauthors found that pregnant cardiologists generally are expected to make up their time away from work before they go on leave. "Cardiologists were not getting the maternity leave that they are legally entitled to," Lee says. "And they were facing pay cuts when they came back from maternity leave, regardless of whether they pre-worked those hours or not. Then, after they gave birth they were still asked to work while on maternity leave." Cardiologists who put in extra clinic service and call time before their family leave were more likely to experience pregnancy complications such as bedrest. "They were working themselves sick at tremendous personal costs, without even realizing that what they were being asked to do is illegal," Lee says.

Because these workplace expectations were not formalized, they were legally flying under the radar, even though they were clearly having a discriminatory effect—only 14.9 percent of practicing cardiologists in 2020 identified as women. Lee emphasizes that working people struggling with issues around childbearing and family leave must push back against unsupportive workplace norms. Resources such as ThePregnantScholar.org and the free legal help line at the Center for WorkLife Law are there to assist workers struggling with questions about balancing employment with childbearing or caregiving.

In the void left by a lack of a national or state policy, changes can be made at the institutional level. Organizations that enforce standards in the field, such as ACGME and funding agencies, can make a big difference, as can individual institutions. In 2019, Mangurian worked with the leadership at the UCSF School of Medicine to change the family leave policy for UCSF medical faculty. UCSF now has 12 weeks of paid leave, regardless of adoption or birth and regardless of the parents' gender or sexual orientation. Ultimately, though, national policies will be the most effective way of ensuring that all workers with caregiving responsibilities at home are able to continue their careers.—*Katie L. Burke*

The orbit of the MOON



Lunar month

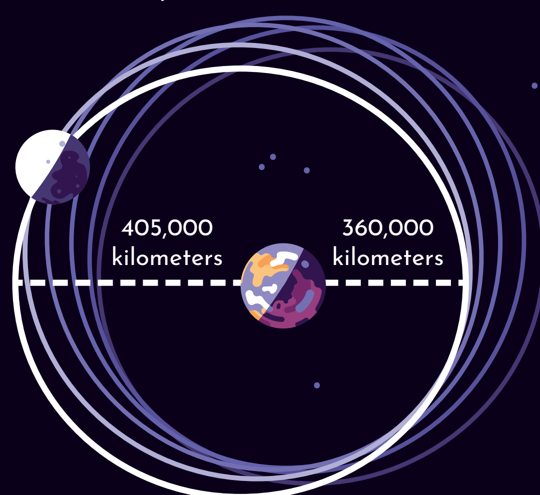
The Moon completes one orbit around the Earth (a *sidereal month*), in 27.3 days. Because the Earth is also orbiting the Sun, it takes two more days for the Moon to complete its cycle of phases (a *synodic month*).

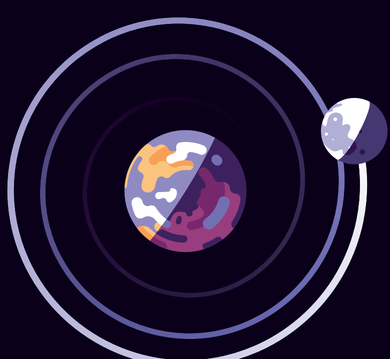
Elliptical orbit

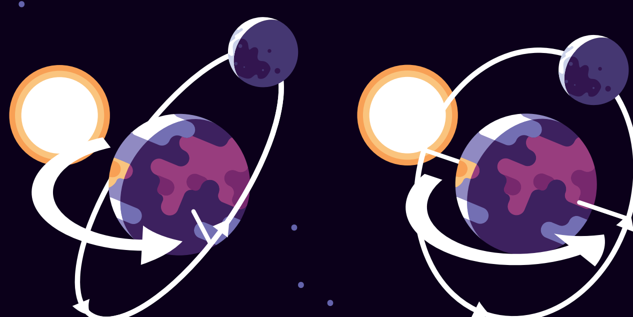
The Moon's orbit has an elliptical (oval) shape, although it looks almost like a circle.

Apsidal precession

The Moon's elliptical orbit orientation changes its orientation, or *precesses*, with a period of 8.85 years.







Drifting away

Every year the Moon's orbit is expanding, taking it farther away from Earth by an average of 3.8 centimeters.

Nodal precession

The plane of the lunar orbit is tilted 5 degrees relative to Earth's orbit around the Sun. It precesses in an 18.6-year cycle.

First Person | Briana Pobiner

Reviewing the Prehistoric Menu

Smithsonian Institution

As a research scientist at the Smithsonian Institution's Human Origins Program, Briana Pobiner has long been fascinated by the role of diet in human evolution. In a 2016 article for American Scientist *("Meat-Eating Among the Earliest Humans," March–April), Pobiner discussed scientific studies that were then beginning to reveal what our human ancestors ate, how they procured food, and what processes they may have followed to make that food palatable and digestible. Further research in archaeology, paleoecology, and other fields, including the analysis of ancient dental plaque, has already done much to contradict the image of our human ancestors as club-wielding carnivores and instead is showing that the genus* Homo *has thrived by being able to eat a wide variety of foods. Pobiner spoke with contributing editor Sandra J. Ackerman about recent developments in the study of human diet. (This interview has been edited for length and clarity.)*

Diets that claim to be based on the eating habits of our Paleolithic ancestors have become popular with many health influencers. How much scientific evidence do we actually have about what early humans were eating?

In the modern conception of a paleo diet, a lot of the emphasis is not on which foods to eat but rather on which ones to avoid—for instance, grains or dairy or legumes—based on the assumption that our ancestors didn't eat these foods, they just ate a lot of meat. The problem is, we don't have good evidence for a whole lot of meat eating, certainly not on the scale suggested by adherents of a paleo diet.

There is good evidence in the fossil record that Neanderthals—our close evolutionary relatives, now extinct—were capable hunters, that they butchered and ate a lot of large animals. But they also ate plants, and they also cooked their food. The idea that any early human species had a very narrow diet is likely not accurate. It was probably our omnivory—the ability to eat a large variety of things—that helped us to survive and to reproduce.

What about the modern human diet?

In terms of our digestive system, humans today are still omnivorous. But when it comes to our evolutionary history, I think one reason we talk a lot about meat eating is that it's so much easier to find evidence of it in the form of fossil animal bones, including those with tool marks that we know for sure are the result of butchering by early humans. It's much harder to find evidence for early humans eating plants or other foods.

Why is that evidence harder to find?

It's really an inherent bias—not a deliberate bias, but the filtering of what gets preserved in the prehistoric record. It's easier to find fossilized animal bones with clear indications of butchering than to find well-preserved plants clearly eaten by early humans, or to examine early human fossils and see if they have any bits of preserved plants stuck in the tartar or calculus on their teeth.

Does plant eating leave characteristic marks on teeth?

Well, sort of. You can tell something about the properties of plants that an animal ate by the pits and scratches on its teeth. The same goes for early human teeth. But when you have *phytoliths* [microscopic particles of silica that form within plants] embedded in the calculus of teeth, that's really a smoking gun that the plant ended up there because someone ate it. (*See "Phytoliths: The Storytelling Stones Inside Plants," March–April 2015.*)

There's also a lot of work now on the analysis of ancient proteins as a window into early human diet. How is that research carried out?

In studies of stone tools that were used to butcher animals, ancient proteins have been extracted from the edges of those tools. For example, at an archaeological site in Jordan that's about 250,000 years old, a research team led by University of Victoria archaeologist April Nowell found blood protein residues from only one kind of animal on each tool. So they know, or at least they can infer pretty strongly, that this tool was used to butcher a horse, that tool was used to butcher a duck, and that other tool was used to butcher a rhino. That's pretty cool.

So the menu for our ancestors of, say, 300,000 years ago could have included a variety of both meats and plants?

Sure! And another important part of early diet we don't often think about would have been fat. One explanation for all these butchery-marked bones is that it may have been not just the meat itself but the bone marrow that early humans were going after, because marrow is so high in fat and calories, which are difficult to find in African savannah ecosystems. That's a testable hypothesis, because you would expect to find a lot of percussion marks from the breaking open of bones to get at the marrow. But when you break open a bone, you get a lot of small shards and pieces that may not always have been collected—especially in the past, because they weren't particularly identifiable in terms of skeletal element or species. So those percussion marks may be on fossils that are missing from our museum collections.

Did human ancestors first start eating meat as scavengers and then at some point go into business for themselves, so to speak? Or did scavenging and hunting take place in tandem?

If the earliest hominins were hunting, I don't know what they were using to hunt with; we don't see spear points in the archaeological record until about half a million years ago. That, I think, is a strong point in support of scavenging first. Another point is that as soon as butchery marks turn up in the fossil record, they are appearing on really large

Briana Pobiner

A fossil bone from the site of Koobi Fora, in Kenya, shows distinct cut marks from a sharp-edged object, an indication that early humans were butchering animals for their meat as long as 1.5 million years ago.

animals. The likelihood that a three-and-a-half-foot-tall hominin with no hunting technology was somehow taking down large animals such as elephants doesn't seem very plausible to me.

Particularly early on, I think scavenging was an important part of how human ancestors got meat and marrow. It's not until much later that you start to see archaeological sites with butchery-marked animal bones from just one or a few species or from just the big adult males, so we really know that Neanderthals or other early humans are going out and specifically hunting this species. They're being more picky about what they're getting. That's a big shift that happened much later in time, probably by around 500,000 years ago.

One more question about scavenging: In a sunny, exposed area, how long would a carcass be safe to eat?

I suspect it depends on whether a carcass is partially in water, whether it's in the sunshine or the shade, whether it's cold or hot, whether it rains a lot, or whatever. My gut instinct, so to speak, is that it's not going to last more than a couple of days before it starts to smell terrible, there are maggots, and you don't necessarily want to eat it. But University of Michigan archaeologist John Speth has a hypothesis that some early humans, particularly Neanderthals, were eating putrefied meat. There are ways to preserve meat that involve this type of putrefaction, and some modern human groups do this routinely today, or did in the recent past. Were early humans following predators around? Did they have a good sense of how quickly they had to get in there before the meat spoiled? I don't know that we'll ever be able to answer those questions. But I do think the question of how long a potential scavenging opportunity is still viable is a good question that, to my knowledge, no one has looked at yet.

How would you go about investigating that question?

You could do it in a fairly experimental way, either with natural scavenging opportunities or by deliberately leaving parts of animals out in different places and monitoring factors such as pathogen load. I'm sure there are aspects you could measure that would tell you whether it was safe to eat or not. Humans have a surprisingly acidic gut, and some people have speculated that we have scavenging in our ancestry because we've had to eat all this food that might have been going off. High levels of acid in our gut could have evolved to deal with food pathogens.

A lot of foods can also be made safe by cooking. How old is the earliest evidence of using fire to cook food?

I would say that the control of fire dates back about a million years, from the site of Wonderwerk Cave in South Africa, which has the earliest evidence for hearths. There are burned bones and plant ashes deep inside the cave. There's no way that evidence is from a natural wildfire, and the remains were very well preserved and not transported by wind or water. And last year, there was a paper published from the site of Gesher Benot Ya'aqov, in Israel, that describes evidence for cooking fish about 780,000 years ago, which I think is the earliest solid evidence for cooking—at least for now.

What evidence is there for the earliest cooking of grains?

At a site called Ohalo II, also in Israel, researchers have found good evidence of sort of "paleo-pitas" being made about 23,000 years ago, with the grinding of grains and cooking them in what was almost like an oven. But some of the phytoliths found on Neanderthal tooth calculus are from plant foods that had been cooked 60,000 years ago. These were precursors of grains including barley, rye, and wheat—not domesticated plants, but related to them.

A lot of new information about early human diet has come to light since you first wrote about meat eating and human evolution for *American Scientist* seven years ago. What's the main point that you'd like readers to take away from the recent research?

The update is that although there is definitely still strong evidence for some meat eating in human prehistory, we have growing evidence now for the eating of plants and fish and even insects. The record shows that omnivory and flexibility characterized early human diets better than a single most important or dominant food source.

How do you answer the question of what early humans were eating that made our brains suddenly get bigger?

I don't know that there will ever be a definitive answer. It very well could be a variety of foods, but it also could be that the specific foods themselves weren't the most significant factor in the evolution of large brains. Maybe it's the grandmothering hypothesis, which holds that provisioning of food by grandmothers allowed grandkids to eat more consistently, and so made it possible for mothers to give birth to babies more often. These grandmothers then passed their "longevity" genes on to their kids and grandkids, and longevity is correlated with large brains in most mammals.

Recently, I held a session of "Skype a Scientist" with a Canadian scout troop of five- and six-year-old girls. One girl asked, "Was vegetarianism invented back then?" And I thought, people in the past ate whatever they could get their hands on. Diets based on a specific rationale or principle are probably a very modern development. ■

In this roundup, managing editor Stacey Lutkoski summarizes notable recent developments in scientific research, selected from reports compiled in the free electronic newsletter *Sigma Xi SmartBrief*: www.smartbrief.com/sigmaxi/index.jsp

Mapping the Insect Brain

The pesky fruit flies circling your trash can may seem mindless, but they in fact have remarkably complex brains. An interdisciplinary team including zoologists, neuroscientists, mathematicians, and engineers has developed a complete neural wiring diagram, called a *connectome*, of larval fruit flies (*Drosophila melanogaster*).

Johns Hopkins University and University of Cambridge

This map is a giant leap forward in brain imaging technology. Researchers have created connectomes for only three other organisms, each mapping several hundred neurons; the larval fruit fly connectome diagrams 3,016 neurons and 543,000 synapses. The team used three-dimensional electron microscopy to create the map. Although the fruit fly larval brain is a far cry from the human brain, which has approximately 100 billion neurons, the two do have some similarities, such as the capacity to learn and to make decisions. Studying the fruit fly connectome may shed light on how all brains operate.

Winding, M., et al. The connectome of an insect brain. Science *379:eadd9330 (March 10).*

Extraterrestrial Origins of Life

One of the four nucleotide bases in RNA has been identified in a sample from the asteroid Ryugu. This finding strongly suggests that asteroids delivered the ingredients for life to Earth. The Japanese Aerospace Exploration Agency Hayabusa2 probe collected two samples from Ryugu in 2019, one from the surface and the other from the subsurface. Both samples contained *uracil*, one of the components of RNA, as well as other organic molecules, such as amino acids and *nictonic acid*, the main component of vitamin B3. Ryugu is a *carbonaceous* (or carbon-rich) asteroid, and the sample study confirmed that these asteroids have a similar composition as a rare type of meteorite called *carbonaceous chondrites*. These meteorites struck Earth long ago, which could have delivered prebiotic compounds to the young planet; however, it is difficult to analyze the chondrites because they have been contaminated by the biosphere. The samples from Ryugu prove that the elements of life were—and are—present in outer space.

Oba, Y., et al. Uracil in the carbonaceous asteroid (162173) Ryugu. Nature Communications *14:1292 (March 21).*

Naraoka, H., et al. Soluble organic molecules in samples of the carbonaceous asteroid (162173) Ryugu. Science *379:eabn9033 (February 24).*

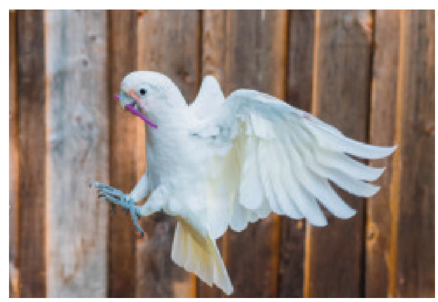
Squid-Inspired Windows

Researchers are taking a cue from nature to create building materials that can adjust to achieve indoor climate control without running the HVAC. A team of materials scientists, engineers, and architects at the University of Toronto sought a product that could selectively filter light and heat, and they found inspiration in the multilayered skin of squid. Some species of squid can actively camouflage by distributing pigments through their skin to change colors, create patterns, and increase reflectance. The team used a similar mechanism to create a window that can independently adjust its filtration of visible light and infrared heating. This technology would allow a person to sit by the window and read a book with plenty of light without getting hot. Inspired by the squid's skin, the researchers created a multilayered material. Each layer is *microfluidic*, meaning it is composed of tiny channels of liquid containing specialized pigments that either transmit, absorb, or reflect light. Adjustable pumps control the amount of pigment in each layer, so a user could fine-tune the amount and intensity of light and heat entering a building. Heating and cooling buildings is one of the most energy-intensive activities worldwide, and because that energy often derives from fossil fuels, it is a significant contributor to climate change. According to the researchers, their technology could reduce a building's energy expenditure by more than 43 percent, which would not only reduce emissions but also put a significant dent in people's energy bills.

Kay, R., J. A. Jakubiec, C. Katrycz, and B. D. Hatton. Multilayered optofluidics for sustainable buildings. Proceedings of the National Academy of Sciences of the U.S.A. *120(6):e2210351120 (January 30).*

Handy-Birds Carry Tool Kits

Cockatoos have joined humans and chimpanzees as the only animals known to carry and use multiple tools. Researchers had previously observed wild Goffin's cockatoos (*Cacatua goffiniana*) carrying tools, such as specialized sticks, in their native Indonesia, but it was not clear whether this was a deliberate or coincidental behavior. A team of evolutionary and behavioral biologists at the University of Vienna tested 10 captive Goffin's cockatoos to see whether they carried and selectively used multiple tools to complete tasks. They gave the birds three distinct tools—one for wedging, another for cutting, and the third for spooning—which had to be used in sequence to open a container of cashews. The cockatoos had varying degrees



Thomas Suchanek / Goffin Lab

of success over three tests of increasing difficulty (and one, Dolittle, chose not to participate). Seven cockatoos used tools to complete the first task, five succeeded at all three tasks, and three of the birds consistently transported their tool sets to solve the final puzzle. Although a minority of the cockatoos deliberately used a tool kit, the three that did demonstrated that the species has the capacity not just to solve a puzzle, but also to plan and execute a sequence of tasks in the correct order, which is a complex cognitive skill. The researchers next plan to explore the birds' ability to anticipate future events and adapt to changing circumstances.

Osuna-Mascaró, A. J., M. O'Hara, R. Folkertsma, S. Tebbich, S. R. Beck, and A. M. I. Auersperg. Flexible tool set transport in Goffin's cockatoos. Current Biology *33:849–857 (March 13).*

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The Human Factor in Floods

Vulnerability to glacial lake floods depends on not just geology but also climate change, population exposure, and social infrastructure.

When Lake Palcacocha, a glacial lake in Peru, suddenly burst in 1941, releasing 8 to 10 million cubic meters of water, the resulting flood killed an estimated 6,000 people, and the water and debris destroyed about a third of the town of Huaraz, 23 kilometers away. Although Peru implemented a lauded engineering program in the decades that followed to stabilize glacial lakes, climate change and political shifts in the region have brought the danger level back up. "That town has been rebuilt in almost exactly the same location, and now it's much more populous. That's particularly scary," says Thomas Robinson, a disaster risk specialist at the University of Canterbury in New Zealand. This example shows how the danger from such *glacial lake outburst floods* (or GLOFs) isn't just a matter of a physical hazard, but varies with the local population level and the availability of government support in the region. "Without adding any human dimensions, hazard parameters aren't very accurate or useful," says Caroline Taylor, a PhD

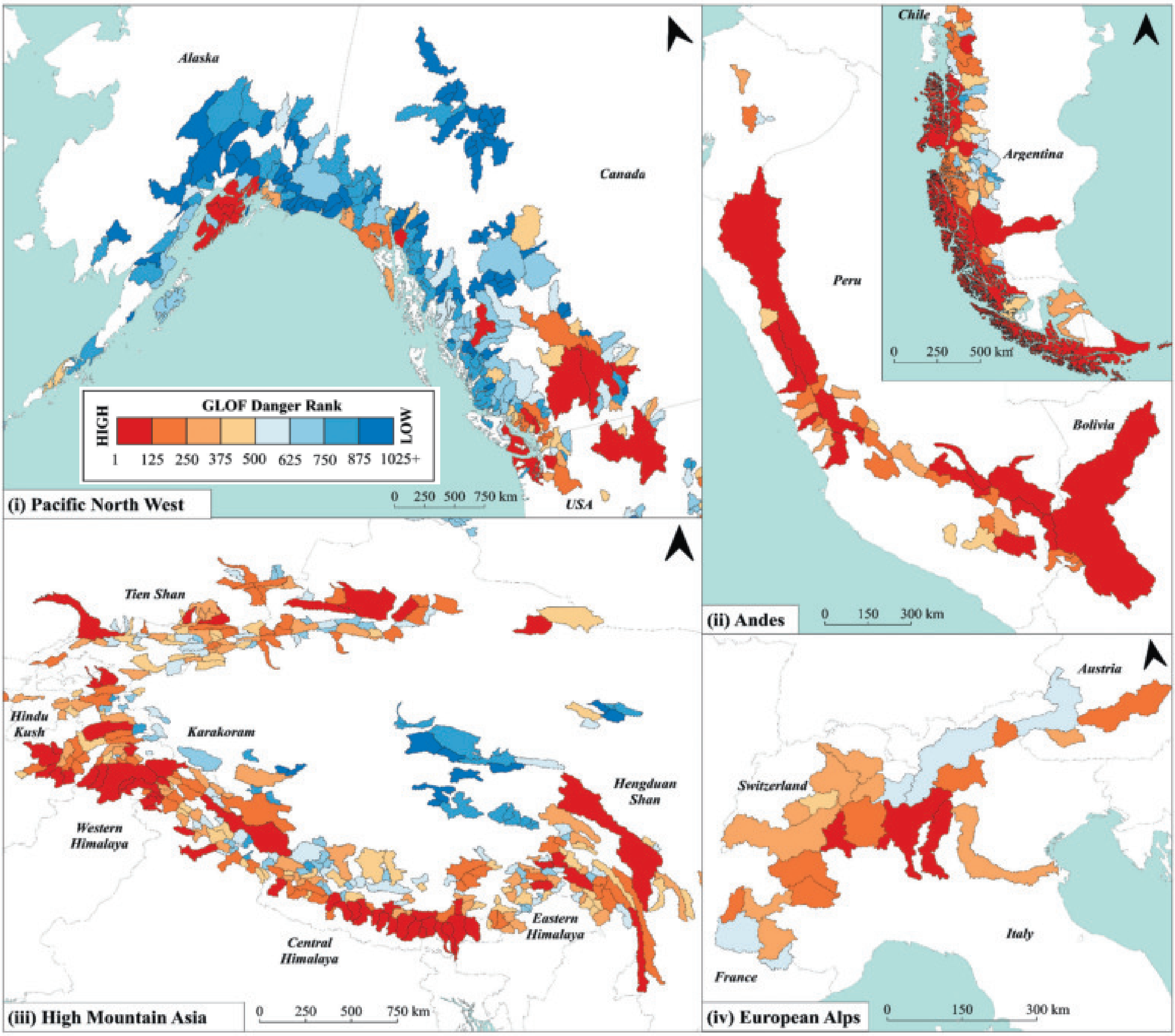


Photo: J. Rachel Carr. Map: C. Taylor et al., 2023, *Nature Communications* 14:487.

student in physical geography at Newcastle University in the United Kingdom. Taylor, Robinson, and their colleagues have used satellite data to identify 1,089 river basins across the globe that contain glacial lakes. They factored in the exposed populations, and used known indices of corruption, human development, and social vulnerability to rank each of these basins on the danger that a GLOF would pose to people in the vicinity (*see the maps above*). As the team reported in *Nature Communications*, they found that about 15 million people worldwide are exposed to potential GLOF impacts. More than half of those people live in four countries: India, Pakistan, Peru, and China. (The 2022 floods in Pakistan, however, were triggered mostly by abnormally large monsoons.)

The high mountain regions of the Himalayas are well known for GLOFs, but the team found similar dangers in the Andes, although there are relatively fewer studies of that region. Other surprising results from the study include potential vulnerability in places such as Bhutan (including the glacial lake at the foot of the mountain called Jomolhari, shown in the photo on the facing page). The number of people who would be affected by a GLOF in Bhutan is low compared with larger countries, but it is a high percentage of the population, upping the danger score. "The way to think about that is, if you have a GLOF, how many people have you got to respond? In Bhutan, you could have a single GLOF that affects a large proportion of the country. Suddenly, their ability to respond is massively impacted," Robinson says.

GLOFs are tightly linked to climate change. Worldwide, glaciers are projected to lose up to half of their mass to melt by 2100. But as glaciers recede, growing populations move closer to them, looking for farmland, water, and hydroelectric power. Limiting climate change will help slow the growth of glacial lakes, but Taylor notes that each location varies in geology and politics, requiring a different combination of early warning systems, engineering solutions, and land-use planning. "Unfortunately, there is no single solution, and what is appropriate in one location may not work in another," she says. Robinson notes that the team's goal is to help focus research efforts on the most potentially dangerous glacial lakes. "If we can go there and show that actually those lakes are not going to burst, great," he says. "But until we've done that, we don't know."—*Fenella Saunders*

Getting Tough with Ionogels

A newly developed chemical process unites ionic liquids and polymers to make strong gels that could be used in batteries, robotics, and more.

Meixiang Wang, Jian Hu, and Michael D. Dickey

Scientific discoveries sometimes arrive as a truly thrilling surprise. That's what happened back in 2019, when our research team was mixing common polymers—long, chain-like molecules containing repeating chemical building blocks—with liquids to make a material that could be used in a pressure sensor. What we eventually produced looked like a mundane piece of transparent, flexible plastic. But when we examined its properties, we were shocked.

Although the material contained about twice as much liquid as polymer, it was remarkably strong: A small strip no thicker than a credit card could lift a 1-kilogram weight without breaking. When we cut the strip in half and then brought the pieces back together again, a little heat healed the rift so well that the strip could continue its weight-lifting program. On top of all that, it even conducted electricity. It turned out that we had created an unexpectedly robust material, known as an *ionogel*.

Ionogels are a relatively recent addition to a much broader family of gels. All gels are made from networks of polymers surrounded by a liquid solvent. Water-based gels, known as *hydrogels*, are a staple of everyday life: Contact lenses, tofu, and gelatin desserts are all hydrogels. Yet most synthetic hydrogels are weak and prone to drying out, which rules out many potential applications. Ionogels, which substitute ionic liquids for water, show great promise in overcoming these drawbacks. Our newfound material may help realize that promise.

Ionic liquids are salts in liquid form made from components called *ions* that carry positive or negative charges—as are many other familiar compounds, such as table salt (a compound composed of positively charged sodium ions and negatively charged chloride ions). Unlike most salts, however, ionic liquids have low melting points, and many are liquids at room temperature, making them useful as solvents, lubricants, or catalysts. Combining the versatile properties of ionic liquids and polymers in tough ionogels could produce a range of materials with exciting applications in batteries, robotics, and medical devices.

Researchers have been hunting for tough gels that don't lose their liquid, and that conduct electricity without breaking down. Ionogels seem to fit the bill perfectly.

Until recently, most known ionogels had poor mechanical properties, and strategies to toughen them generally required complicated chemical methods. But our tough ionogels are easy to make. We can produce them by combining simple chemicals and illuminating them with ultraviolet light for a few minutes. Such rapid synthesis means we can use 3D printing to form these ionogels into specific shapes, such as robotic fingers.

We are now learning how to tweak the chemical characteristics of polymers and ionic liquids to fine-tune the properties of the ionogels they form. These design principles give us a road map for creating many more ionogels that are as stretchy or tough or stiff as we need. What began as a lucky discovery has opened up a new chapter in materials science.

Network Effects

Chemists and materials scientists have long dreamed of making tough, long-lasting gels. Some natural hydrogels are surprisingly strong and durable, such as the cartilage found in the connective tissue in our bodies. For years, chemists and engineers have sought synthetic gels that can match these properties.

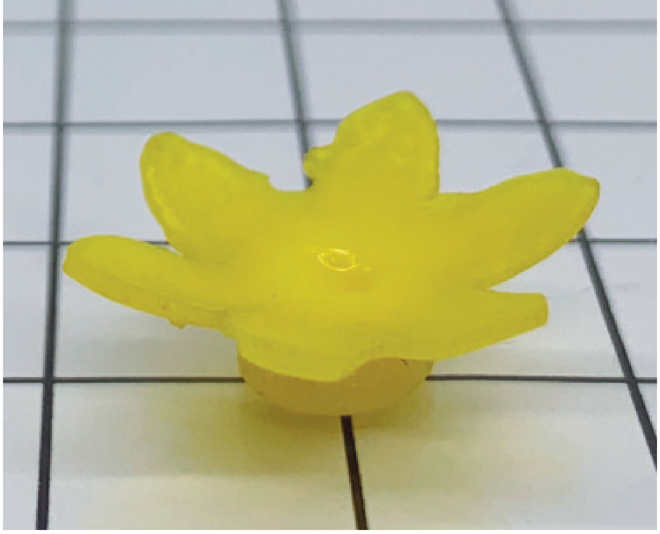
To understand what makes a gel weak or strong, researchers like us take a close look at its structure. In most gels, the polymer strands are almost entirely surrounded by their partner solvent, meaning there are few direct interactions between the polymer strands, so it's easy to pull them apart and

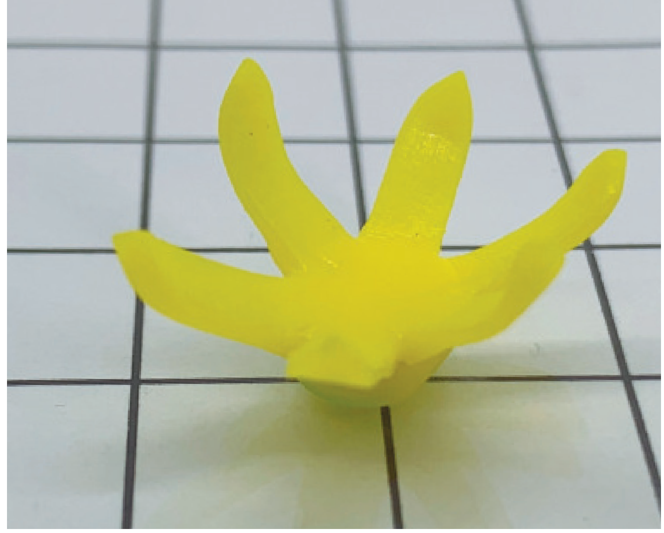
QUICK TAKE

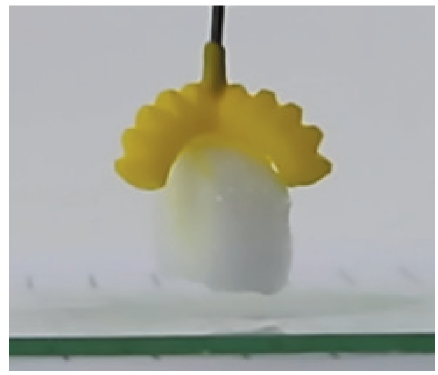
Gels are ubiquitous materials that combine polymers with liquids; water-based gels are found in contact lenses, gelatin desserts, and the cartilage in our bodies.

Instead of water, ionogels are composed of *ionic liquids*, which have a low melting point, conduct electricity, and do not evaporate as easily as water.

A simple new method to make tough ionogels could now help scientists use these materials in diverse applications such as medical devices, robotics, and batteries.







Ionogels blend the remarkable properties of polymers with those of ionic liquids. The authors have devised a simple, light-based method for making tough ionogels, meaning they can now be 3D printed in a variety of forms, including flowers (*above*) and a robotic gripper (*right*).

M. Wang et al., 2022.

stretch the gel. In contrast, tough gels found in nature have evolved complex polymer networks that feature more connective bonds between the strands. These are not covalent chemical bonds (like the bonds that bind atoms within the strand itself) but somewhat weaker connections such as hydrogen bonds, which result from small differences in electrical charge between parts of the polymer. Collectively, these hydrogen bonds help to make the gel less stretchy. The polymer networks also help to spread stress over a wider area, preventing cracks from racing through the material and holding the gel together under heavier loads.

In 2003, researchers led by materials scientist Jian Ping Gong at Hokkaido University in Japan used these principles to create the first synthetic hydrogel that was as tough as cartilage. Their hydrogel relied on intertwined networks of two different polymers. The first polymer was relatively brittle and contained short strands that would break apart when the material was stretched, helping to dissipate energy and prevent any cracks from spreading. The second polymer network had longer strands and provided an elastic, 3D framework to help distribute stress while holding the gel together.

Gong's hydrogel was a landmark discovery, because it showed how a soft, stretchy material can be combined with a stiff, brittle material to generate toughness. The innovative work sparked a rush to develop other tough hydrogels, which might eventually be used as replacement materials for worn cartilage, or in biomedical devices.

Unfortunately, hydrogels face several major problems. The water inside the gel can evaporate, for example, causing the gel to shrink and weaken. Contact lenses are usually shipped in pouches containing water to prevent such dehydration, and hydrogels used as medical implants are naturally bathed in the body's own water. But the need to stay wet severely limits other applications of these materials.

Hydrogels also have limited usefulness in electrical applications. Some researchers have sought to develop gels that could be used as safer and more effective electrolytes, the materials that carry charge between a battery's electrodes. But hydrogels are unsuitable for the job, because even modest voltages split their water molecules into gaseous hydrogen and oxygen, which degrades the gel and poses a fire hazard.

For all of these reasons, researchers have been hunting for tough gels that don't lose their liquid, and that conduct electricity without breaking down. Ionogels seem to fit the bill perfectly.

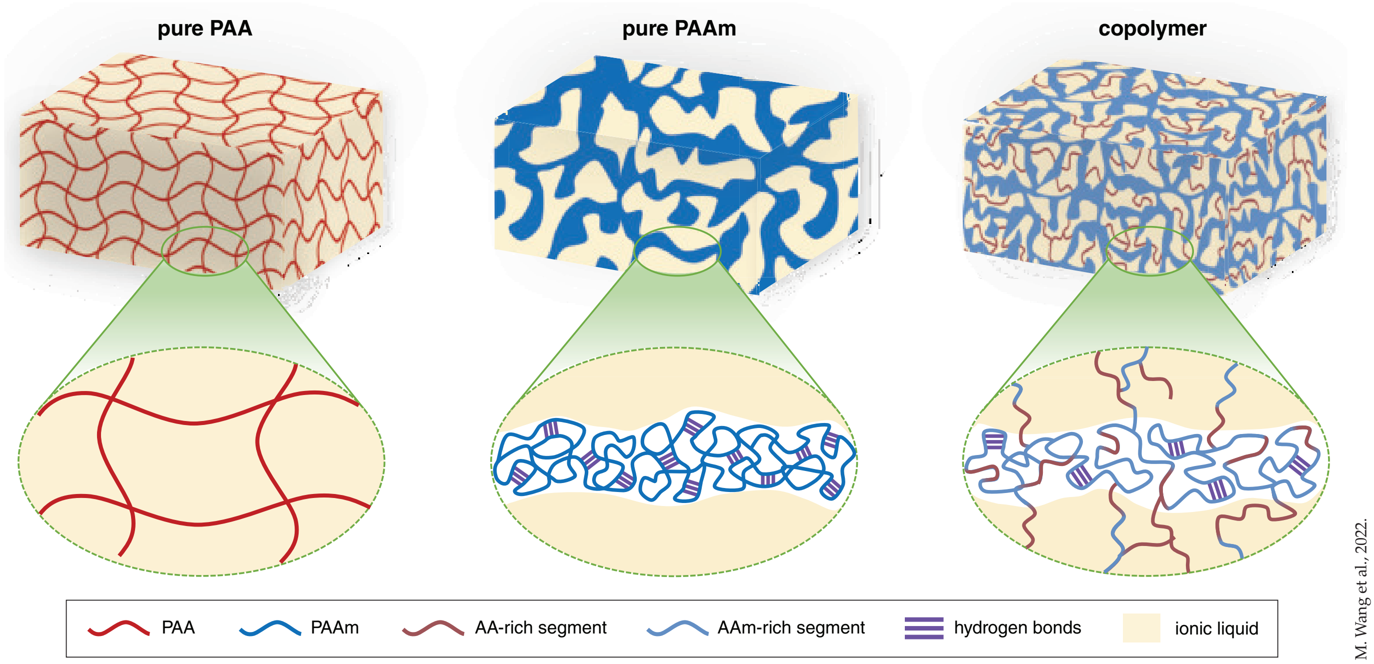
Ionic Liquids to the Rescue

Ionogels owe many of their amazing properties to their ionic liquids. The liquids' positive and negative ions—known to chemists as cations and anions—can be charged molecules, or they can be atomic ions such as the chloride in table salt. Ionic liquids are good electrical conductors because their ions can move around, allowing electrical currents to flow, and they can typically withstand voltages at least four times as high as the voltage that causes water to break down. The strong attraction between the ions in these liquids means they do not evaporate easily, even when heated to several hundred degrees Celsius.

Ionic liquids are also a source of tremendous variety, because the cations and anions can be modified independently. Thus, in principle, chemists can combine cations and anions in trillions of different ways, using specific ions to fine-tune the ionic liquid's properties. Some ionic liquids are designed to repel water, for example, whereas others absorb water.

Chemists have been working on ionic liquids for more than a century. But in 1993, a team led by Masayoshi Watanabe at Yokohama National University combined ionic liquids with polymers to make the first ionogels. Since then, researchers have experimented with ionogels as adhesives, components in wearable electronics, and electrolytes in batteries. Yet these applications remain confined to the laboratory, in part because ionogels have not been tough enough for practical applications.

Despite considerable effort, chemists and materials scientists have found it difficult to improve the mechanical properties of ionogels. We still don't fully understand the interplay between the ions and polymers in ionogels, which makes it tricky to select the right ingredients needed to create a tough ionogel. Some teams have attempted a workaround by preparing gels using other solvents, then replacing those solvents



A network of the polymer polyacrylic acid (PAA) dispersed in an ionic liquid forms an ionogel that is soft and transparent (*left*). A polyacrylamide (PAAm) ionogel contains dense clusters held together by hydrogen bonds, making the material brittle and opaque (*middle*). By mixing both of the polymers' building blocks—acrylic acid (AA) and acrylamide (AAm)—the authors created a copolymer ionogel (*right*) that was tough and transparent.

with ionic liquids. This solvent-exchange method has seen some success, but it is time-consuming and costly, and involves organic solvents that are not environmentally friendly.

Our new discovery is significant because it offers a much simpler route to tough ionogels. At the time, we were trying to make an ionogel based on a common polymer called *polyacrylic acid* (PAA). This white powder can absorb many times its own weight in water to become a soft gel, and is used to soak up urine in baby diapers.

Rather than starting with complete strands of PAA, we dissolved the polymer's building blocks—called *monomers*—in an ionic liquid and then used chemical reactions to link them together into full strands.

The monomer for PAA is a small molecule called acrylic acid. We added it to a clear, colorless ionic liquid called 1-ethyl-3-methylimidazolium ethyl sulfate and then triggered the polymerization reaction by shining ultraviolet light at the mixture. Unfortunately, the transparent ionogel we formed was a disappointment: soft, sticky, and difficult to handle. Next, we tried another common monomer called acrylamide, which is similar to acrylic acid but contains a nitrogen-based chemical group. Although polyacrylamide (PAAm) can toughen some hydrogels, the ionogel we formed was brittle, opaque, and white.

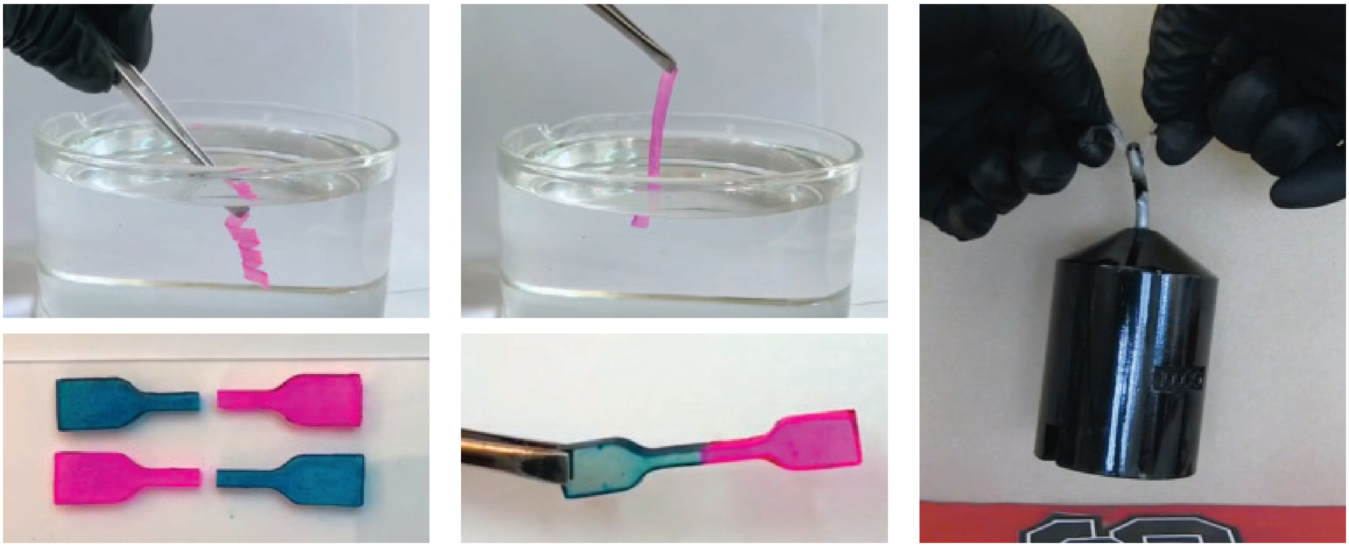
Out of curiosity, we started mixing the two monomers together before polymerizing them, hoping to form a *copolymer* that contained both monomers within the same polymer strands. This time, the result was astounding. If we chose the right ratio of monomers, we could produce an ionogel that was extremely tough and also transparent. We found that a 0.2-gram sliver of the ionogel could support a load 5,000 times its own weight. It was at least as tough as cartilage or natural rubbers, and it outperformed most synthetic hydrogels. Compared with other common ionogels, this copolymer ionogel is about 10 times as strong, 50 times as stiff, and 25 times better at inhibiting the growth of cracks.

The ionogel was at least as tough as cartilage or natural rubbers, and it outperformed most synthetic hydrogels.

To investigate the origins of these properties, we studied the structures of the two substandard ionogels we had previously formed from PAA and PAAm. PAA is highly soluble in our ionic liquid, so the polymer strands are evenly dispersed in the ionogel. Although this solubility makes the gel transparent, it diminishes the interactions between the polymer chains, making the gel soft and stretchable but weak.

In contrast, PAAm is poorly soluble in the ionic liquid, so the polymer chains clump together into dense clusters called *domains*. These domains are large enough to scatter light and make the ionogel opaque—the same reason that small globules of fat and protein make milk white. Polymer strands within the domains are bound together by hydrogen bonds, which make the ionogel stiff yet brittle.

Finally we began to understand why our new material had such marvelous properties. Polymerizing both monomers in the ionic liquid at the same time led to the formation of a copolymer network with a hybrid architecture. Each polymer strand contains a mixture of the two monomers, giving it the name *poly(acrylamide-co-acrylic acid)*. The resulting structure resembles an archipelago of sturdy islands that are surrounded and connected by a soft, rubbery sea. The islands are dense clusters of polymer rich in acrylamide units, while the sea of ionic liquid hosts flexible polymer strands containing more acrylic acid units.



M. Wang et al., 2022.

The authors' copolymer ionogel has remarkable properties, including shape memory (*top*), self-healing (*bottom*), and strength (*right, with a 1-kilogram weight*).

When we stretch our new ionogel, the hydrogen bonds within the rigid domains break first and dissipate some of the strain energy. Meanwhile, the rubbery sea can stretch easily and distribute stress through the whole material. It's a team effort that relies on the same kinds of molecular interactions seen in Jian Ping Gong's copolymer hydrogels, and it makes our ionogel tough and stretchable.

Ionogel, Heal Thyself

The novel structure of our copolymer ionogel also explains its intriguing self-healing nature. We can cut the ionogel in half and then reunite the pieces simply by bringing them together and heating them to about 60 degrees Celsius. The warmth helps the rigid domains loosen up, allowing their polymer chains to mingle with the ionic liquid solvent. When the two cut pieces are placed in contact, the polymer strands can reach out across the gap to meet other strands on the other side. Once cooled, they clasp together to form new domains that hold the material together.

This behavior gives our ionogel another valuable property known as *shape memory*. If we heat the ionogel, stretch it, and allow it to cool, the newly formed domains lock it into its new shape. But if we heat the ionogel again, the wider network of polymer strands pulls the material back to its original shape, almost as if it "remembers" what it used to look like.

Self-healing and shape memory could both be useful in practical applications. Self-healing can help to repair cracks or damaged parts in an ionogel, extending its lifetime. And biocompatible ionogels with shape memory properties could be useful for medical implants, such as the vascular stents that are used to open up narrowed blood vessels inside patients.

The ability of ionogels to conduct electricity without breaking down could also make them useful for entirely different kinds of products, such as battery electrolytes. Most existing battery electrolytes contain organic solvents that are toxic and flammable, so researchers have been looking for alternatives. Any practical replacement material would need to be highly robust, because charging and discharging a battery causes tiny fingers of metal called *dendrites* to grow from the battery's anode. If the dendrites grow too long into the electrolyte, they can cause dangerous short circuits.

Most gel-based electrolytes are too weak, but ionogels could be tailored so that they are stiff enough to fend off the dendrites. Ionogels can also withstand temperatures of –70 degrees Celsius to 350 degrees Celsius without freezing or boiling, so ionogel-based electrical devices could potentially be used in extreme environments, from the deserts to the Earth's poles, or even in outer space.

The simplicity of our method for creating these tough ionogels also bodes well for future applications. We have used the same procedure with other combinations of monomers and ionic liquids, creating a range of ionogels with different properties, and other research teams have adopted our method. We have also used a 3D printer to form ionogels into various shapes, including a tough, flexible, three-arm gripper that could be used as a robotic hand. In the future, we hope to explore other potential applications, including hollow parts for a pneumatic robot arm and flexible sensors for wearable medical devices.

For now, these are all proof-of-principle demonstrations that are a long way from becoming commercial devices. But as researchers learn more about how to adjust the chemical makeup of ionogels and fine-tune their performance, we expect to discover many more unique materials with innovative uses.

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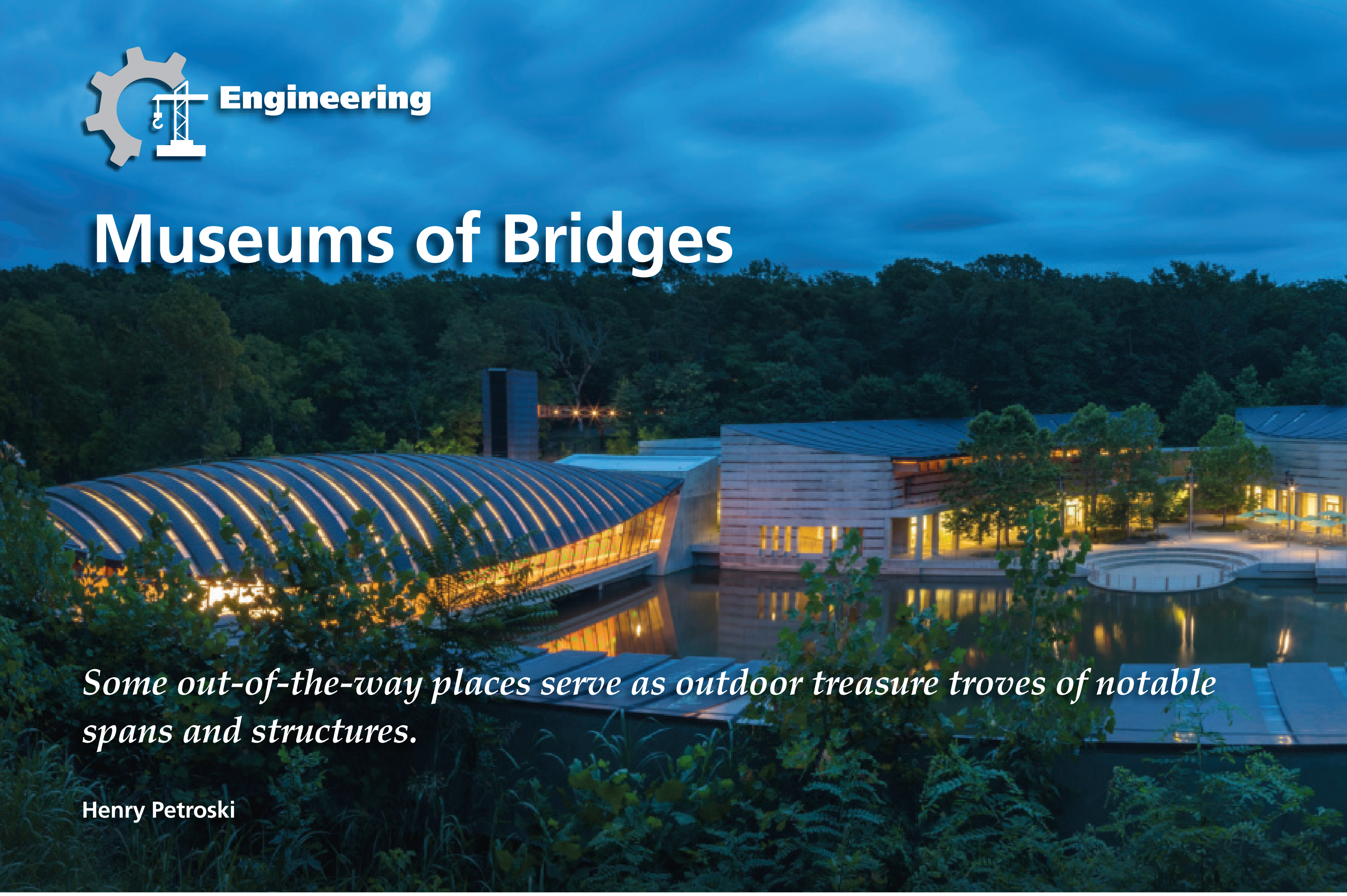

Engineering

Museums of Bridges

Some out-of-the-way places serve as outdoor treasure troves of notable spans and structures.

Henry Petroski

Many cities—such as New York, Pittsburgh, Chicago, St. Louis, London, Paris, Venice, and Istanbul—strike me as veritable museums of bridges, not only because they display large collections of unique works of structural art, but also because these works represent a range of historical periods and genres created by a variety of structural artists working in different media. I began to wonder if "museum of bridges" was a term commonly used in conjunction with such cities, so I searched for it online. The first thing that came up was the Crystal Bridges Museum of American Art in Arkansas. This result was not what I was expecting, but it certainly does fit the search terms and, upon reflection, is not an inappropriate place to begin thinking about museums of anything. Indeed, the result reminded me that my most memorable experiences with so many human-made things—cities, bridges, buildings, museums—have been enhanced by my being introduced to them by extraordinary people who wanted to share their knowledge and appreciation of them.

Bridge aficionados love to photograph and show off their favorites. Robert Cortright, a retired banker from Oregon, calls his hobby of finding and photographing beautiful spans "bridging," and he has published several books with that title that are as strikingly illustrated as the works in the catalog of an art exhibit. Historic bridge enthusiasts are also known as *pontists*, after the French word for bridge. Eric DeLony, longtime chief of the Historic American Engineering Record program of the U.S. National Park Service, was a pontist extraordinaire. In the United Kingdom, the engineer-historian Roland Paxton has long enabled me and many an American bridge lover to experience such rare privileges as standing atop the great steel cantilever rail bridge across the Firth of Forth in Scotland, from which one can observe Edinburgh in the distance.

It was an American engineering colleague of mine named Augustine J. Fredrich, whom everyone called Jay, who personally introduced me and my wife, Catherine, to the Crystal Bridges Museum. Jay was born and bred in Arkansas. After graduating from the University of Arkansas, he began a long and distinguished career with the U.S. Army Corps of Engineers, culminating in a stint as a congressional fellow that led to his serving as senior policy analyst in the Office of the Chief of Engineers and director of the Corps's Institute of Water Resources. Subsequently, he joined the faculty of the University of Southern Indiana and was instrumental in converting a technology program there into a full engineering curriculum. Throughout his career, Jay was keenly interested in history, art, and architecture; he led courses and guided tours of Gothic cathedrals, and curated an exhibit of Joseph Pennell's lithographs, which depict great engineering construction projects such as the Panama Canal.

Tucked in the Corner

The Crystal Bridges Museum is located in the extreme northwest corner of Arkansas, in a city of about 60,000 called Bentonville, which was named

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Crystal Bridges Museum of American Art

The Crystal Bridges Museum of American Art in Bentonville, Arkansas, is situated in a natural ravine carved out by the museum's namesake, Crystal Springs. The museum consists of eight exhibit pavillions connected by covered, glass-sided bridges. The collection was established by Alice L. Walton, daughter of Sam Walton, the founder of Walmart. The museum does not emphasize the corporate connection, but its establishment raised commentary about a throwback to the era of arts institutions founded by industrial philanthropists.

for Thomas Hart Benton, a U.S. senator from the abutting state of Missouri who was a staunch supporter of statehood for Arkansas. Bentonville is more widely known today as the home of the Walton family, whose patriarch, Sam, founded Walmart. It was Sam's daughter, the philanthropist and arts patron Alice L. Walton, who was instrumental in establishing Crystal Bridges, a piece of art in its own right and a repository of some of the most significant art—folk through fine—created in America, from colonial times through the present.

The setting for this world-class museum is a natural ravine (carved out by the museum's namesake, Crystal Springs) and is as counterintuitive as its geographical location in the Ozarks. Nevertheless, its internationally renowned architect Moshe Safdie and equally distinguished engineering firm Buro Happold created a striking multielement design with spring-fed ponds and deciduous trees, which preserved the structure's environmental context at the same time that it overcame the technical challenges that the setting presented. The museum opened on November 11, 2011 (11/11/11), which explains why Eleven is the name of the museum's restaurant.

A week or so before Catherine and I left for Little Rock, I received a phone call from my editor at Harvard University Press. In the ensuing chitchat, he asked me what I was up to those days. When I told him I was heading to Arkansas the next week and then to Alabama the following one, he asked me deadpan, "Why would anyone want to go to those places?" The question took me aback, for I always enjoy learning about and lecturing in new venues, and I may have said something as cliché as, "Because they are there." At the time, I did not know the background or significance of the Crystal Bridges Museum of American Art, nor did I know what I was in store for in visiting the William J. Clinton Presidential Library and Museum in Little Rock.

A Cantilevered Structure

The Clinton complex, which has been described as modernist, was designed by the architectural partnership of James Polshek and Richard Olcott. The original plan for the main building was to have its long side oriented parallel to the Arkansas River, but this design was rotated by 90 degrees so that visitors approaching along the riverbank would have a clear and dramatic view of the structure cantilevered out over the water. The structural skeleton of the cantilever is easily visible through the glass facade, and the combination of interconnected horizontal, vertical, and diagonal members shows it clearly to be a gigantic steel truss. The engineer for the structure was Leslie E. Robertson Associates, whose principal, Les Robertson, began his career as the engineer of record for the Twin Towers of New York's World Trade Center. It was little consolation to Robertson that those majestic towers structurally withstood the 2001 terrorist attack but succumbed to the ensuing fires. In Little Rock, he conquered gravity not vertically but horizontally, with a cantilevered library and museum wing that looks as if it was designed to meet a corresponding half reaching out from the other side of the political aisle. Symbolically, the cantilever evokes presidential candidate Bill Clinton's promise to build a bridge to the 21st century.

Parallel to the Clinton Library cantilever is a complete bridge, which was built in 1899 to carry the Rock Island Railroad across the river separating Little Rock from North Little Rock, at a time when the 19th century was reaching into the 20th. Officially named the Choctaw Bridge when it opened, this Rock Island Railroad Bridge has been converted to a pedestrian crossing and is now considered part of the Clinton Library and Museum complex; as such, it is referred to as the Clinton Presidential Park Bridge. In its original configuration, the main span was movable and could pivot to open up a pair of channels through which river traffic could pass. In the 1970s, the swing span was converted to a lift span. Now, the lift span is in a perma-

Arkansas Democrat-Gazette/Staton Breidenthal

The William J. Clinton Presidential Library and Museum in Little Rock, Arkansas, contains a 420-foot-long (128-meter-long) wing that is suspended on a 90-foot (27-meter) cantilever over the Arkansas River. The park surrounding the building incorporates a historic railroad bridge that is now used as a pedestrian crossing. The cantilever and bridge theme of the complex was chosen to echo Clinton's campaign pledge of "building a bridge to the 21st century."

nently raised position, and the original truss spans flanking it are considered to be the ones of historic significance.

After our visit to the Clinton bridges, Jay gave us a tour of Little Rock historic sites, including Central High School, where the U.S. Supreme Court decision on school desegregation was famously tested in 1957. Then we began the long drive to Bentonville.

An Art Pilgrimage

The opening of Crystal Bridges had been anticipated by the art world, with articles in such newspapers as the *New York Times*, which months before the opening declared that "the era of the world-class museum built by a single philanthropist in the tradition of Isabella Stewart Gardner, John Pierpont Morgan Jr. and Gertrude Vanderbilt Whitney may seem to have passed, but Alice L. Walton is bringing it back." A preview published in the *Washington Post* about a month before the opening seconded the description of "a world-class museum."

The idea for a major museum of valuable American Art outside of what were generally considered to be urbane and cosmopolitan art centers was made public in 2005, when Alice Walton announced her choice of architect and began buying up masterworks. *Kindred Spirits*, by the Hudson River landscape artist Asher B. Durand, was purchased from the New York Public Library for a reported $35 million. According to one of the main art critics of the *New York Times*, "the purchase came early in an extended shopping spree that rattled nerves." The following year, Thomas Jefferson University announced an agreement to sell Thomas Eakins's 1875 painting

The cantilevered library and museum wing looks as if it was designed to meet a corresponding half reaching out from the other side of the political aisle.

The Gross Clinic, which is significant to the history of medicine, jointly to the Arkansas museum and Washington's National Gallery of Art for $68 million, but a massive last-ditch fundraising effort succeeded in keeping the painting in Philadelphia. Nevertheless, such targeted purchases helped to establish Crystal Bridges as "poised to make a genuine cultural contribution, and possibly to become a place of pilgrimage for art lovers from around the world," according to the *New York Times*.

To get to the museum proper, we had to perform the counterintuitive act of taking an elevator down into what appeared to be a courtyard in a hollow. Physically, the museum consists of eight pavilions in which the art is displayed and protected from harmful sunlight and moisture. These pavilions are interconnected by glass-walled corridors—crystal bridges—that provide views of the two large pools fed by the eponymous spring, as well as the surrounding woodland. When viewing the art in each of the galleries, visitors can easily forget they are not in a large metropolitan area but in the Ozarks, although they are quickly reminded of the setting as they cross a bridge to the next gallery. The collection of American art I saw hanging in the Crystal Bridges Museum is as spectacular as any I have seen in any big-city museum, including New York's Metropolitan, Chicago's Art Institute, and Washington, D.C.'s National Gallery. Among the notable pieces in the museum's collection are portraits of George Washington by Gilbert Stuart and by Charles Willson Peale; Norman Rockwell's *Rosie the Riveter*; and works by Georgia O'Keeffe, Jasper Johns, and Andy Warhol, who is represented by a silkscreen of Dolly Parton. There are also significant pieces of sculpture.

Integrated in the Setting

After viewing the art at Crystal Bridges, we set out to return to Little Rock not by retracing our route but by driving due east to view a couple of small chapels in the woods that I had not seen previously, which I hoped would be worth the ride along some rough and curvy backroads. Our main destination was Eureka Springs, a Victorian resort town and spa that since 1980 has been the location of Thorncrown Chapel, a structure of pine and glass that stands 24 feet (7 meters) wide, 60 feet (18 meters) long, and 48 feet (15 meters) high. Although not much larger in plan than a squat 1960s American ranch house, the chapel soars vertically among the trees to what can seem to be cathedral heights. Its architect was E. Fay Jones, who was born in 1921 in Pine Bluff, Arkansas, and educated at the University of Arkansas, where he later taught and became associated with its School of Architecture

(which is now named after him) for the bulk of his career. He participated in Frank Lloyd Wright's workshops at Taliesin, near Spring Green, Wisconsin, and at Taliesin West in Scottsdale, Arizona. Jones became the only disciple of Wright's to win the Gold Medal of the American Institute of Architects (AIA), the organization's highest honor.

As impressive as Jones's career was, it pales in comparison to the first and lasting impression conveyed by his Thorncrown Chapel. Although its dimensions are modest, its open and transparent structure makes it appear as grand as the trees among which it stands, not as an intrusive artificial object of dominance but as an integral and humble part of its setting. It needs no stained glass, for the green of the surrounding vegetation provides color enough. It is not only a piece of architecture and folk engineering—no piece of lumber in the structure is larger than what two workers could carry through the woods—but also a true work of art.

Thorncrown Chapel is said to have been inspired by the Sainte-Chapelle, the light-filled family chapel of medieval French kings located on the Île de la Cité in Paris. Jones playfully described Thorncrown's style as "Ozark Gothic." The AIA listed the structure as fourth on its list of top 10 buildings of the 20th century, and during his lifetime Jones was recognized as one of the top 10 living architects of that century. When Thorncrown was barely 20 years old, it was added to the National Register of Historic Places, a recognition normally reserved for structures at least 50 years old. Experiencing Thorncrown Chapel should be reason enough for wanting to visit Arkansas.

REUTERS/Alamy Stock Photo

Thorncrown Chapel's architect, E. Fay Jones, would playfully describe the structure's style as Ozark Gothic. The building, with 425 windows containing 560 square meters of glass, was designed to integrate with the natural setting.

Although Thorncrown Chapel's dimensions are modest, its open and transparent structure makes it appear as grand as the trees among which it stands.

Pontists in Person

When I set out to write about museums of bridges, I did not expect to travel to Arkansas, but I was sure I would go to Portland, Oregon. On one of my many visits to Portland, I was fortunate to be given a tour of the city's collection of Willamette River spans by local "Bridge Lady" Sharon Wood, who literally wrote an exhibit catalog when she authored *The Portland Bridge Book* in 1989. Among these historically significant structures designed by world-class engineers are the St. Johns Bridge, a suspension bridge designed by David Steinman; the Steel Bridge, a double-deck vertical lift drawbridge, designed by the engineering company Waddell & Harrington; and the Broadway Bridge, the world's longest twin-leaf bascule drawbridge, designed by Ralph Modjeski. A newer bascule, the Morrison Bridge, is notable for having allowed the Bridge Lady to take tour groups into the operator's house and down into the mechanical pit while the 10-meter-diameter gears and 860-metric-ton concrete counterweight were at work opening the bridge.

Sharon Wood's private life has also revolved about bridges. It was while gathering background for a newspaper story on the 20th anniversary of the opening of the tied-arch Fremont Bridge that she met her future husband, the engineer Ed Wortman, who had worked on the bridge during its construction. She and he later teamed up to write *The Big & Awesome Bridges of Portland & Vancouver: A Book for Young Readers and Their Teachers*, which contains accurate drawings of the bridges and instructions for building and testing models of them. It was published in 2014, after years of fundraising to produce the book and make it available to public schools and libraries in the region.

Bridge devotees such as Sharon and Ed curate collections of bridges formally and informally in places large and small, known and obscure, around the world. Some of their collections are so extensive that they are not confined to a single city gallery, but like the art of the Crystal Bridges Museum, are best viewed by moving from pavilion to pavilion. Such are the bridges of the Mississippi, the Monongahela, the Allegheny, the Ohio, the Cuyahoga, the Hudson, the Niagara, the Thames, the Tyne, the Seine, and the Yangtze, not to mention the bays of San Francisco and Chesapeake. There are also museums of bridges located in New York's Central Park and along Connecticut's Merritt Parkway. Over the years, I have accumulated excellent catalogs of these exhibits, and I hope that any bridges that I have yet to view I will also be able to explore with a local enthusiast.

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Perspective

Wildlife Surveys Out of Thin Air

Capturing genetic material in water, air, or parasitic blood samples can be used to noninvasively tally the wildlife in an area.

Asia Murphy

In 2022, Nina Garrett of York University and her colleagues stood outside of a classroom that they were using as a makeshift field lab in Belize. Filters they had made using jerry-rigged computer fans sucked in air, trapping dust, hair, shed skin cells, and other particles on HVAC filter material. Later, they processed the samples collected on the filter, amplified the tiny DNA strands using a process called *PCR—polymerase chain reaction*, a foundational innovation in genetics—and matched the samples to a reference library. Using these simple fans and filters, the team was able to determine that many species of bats had been in this classroom, including Jamaican fruit-eating bats and ghost-faced bats. There were also kinkajou, long-tailed arboreal carnivores related to raccoons, detected in the classroom. And horses. And eastern small-footed bats, which are endangered and found only as far south as central Arkansas, more than 2,000 kilometers away.

What in the world were such animals doing in that classroom? Garrett and her colleagues had been working to assess how well their method detected animals that they knew had recently been there as part of their field study, but they found much more than they'd bargained for.

Welcome to the world of *environmentally obtained DNA* (or *eDNA* for short).

Terrestrial leeches, such as the one below (*Haemadipsa* spp.) straddling the face of a tree frog (*Rhacophorus* spp.), are increasingly being used as a source of invertebrate-derived DNA, or iDNA, to assess wildlife biodiversity in the rainforests of Asia, Australasia, and Madagascar where they are found. Such environmentally obtained DNA or RNA, called eDNA and eRNA for short, can provide a variety of clues about an area's wildlife.

Courtesy of Andrew Tilker (IZW)

QUICK TAKE

Environmentally obtained DNA (eDNA) has been used to study wildlife since the 1990s—first from scat or fur, and more recently from trace amounts in air, water, and parasites.

Environmental DNA can be very sensitive, picking up cross-contaminants or long-dead organisms. For a recent snapshot of living biodiversity in an area, researchers can use eRNA.

Using eDNA and eRNA in wildlife surveys is still in its infancy, and researchers cannot yet use genetic material to estimate species abundance or density.

The first time I heard about eDNA, I immediately thought: Nah. Detecting traces of DNA in air or water seemed like science fiction, too good to be true. As a person who studies wildlife using camera traps, I support maximizing the use of noninvasive techniques when studying wildlife. Researching animals without catching them is ideal, from a scientific and ethical point of view, because getting trapped stresses out an animal and affects its biology and behavior. I understood camera traps. An animal walks in front of a camera, breaks an infrared beam, and the camera snaps a picture of the animal. The idea that fragments of DNA from the air could indicate an animal's recent presence just seemed too far-fetched to me.

However, I was already familiar with eDNA, despite never realizing it. As part of my work, I had walked up and down Appalachian dirt roads, picking up scat (read: poop), which would later be tested to determine whether it came from coyotes. I had read papers documenting how researchers used shed feathers to look at genetic relatedness among eastern imperial eagles. Biologists used environmental genetic material as early as the 1990s; indeed, it is a key tool in ecology.

POSSIBLE DATA	eDNA	eRNA
population-level		
presence/absence of detectable taxa	✔ (includes dead organisms)	✔
species abundance	TBD	TBD
allele or haplotype frequency	✔	TBD
life history stages	✘	✔
phenotypes	✘	✔
sex ratios	✘	✔
community-level		
recent, metabolically active assemblages of organisms	✘	✔
detection of dead organisms	✔	✘
diagnostics		
organism health	✘	✔
stress response	✘	✔

Barbara Aulicino, adapted from Yates et al. 2021

Environmental DNA can detect both living and dead organisms. Unlike DNA, RNA is more actively involved in protein expression, which happens only in living organisms, and it degrades much faster in an environment. That means eRNA has to be collected and analyzed rapidly, a challenge that has limited its use so far, despite the important information it can provide.

A Brief History of eDNA

In addition to the current focus on sampling DNA in air and water, eDNA includes genetic material we receive from scat and hair. The first published studies that derived genetic information from scat and hair were two four-paragraph "scientific correspondences" published in 1992 in the journal *Nature*. Almost charmingly archaic, they begin with "Sir," like the old-timey journal articles of the 1800s. The first correspondence, published in July of that year by ecologists Pierre Taberlet and Jean Bouvet, announced that they had derived DNA from bear fur. The second, by biologist Matthias Höss and colleagues, followed close behind in September, announcing that they had derived DNA from bear scat.

As if publishing in the same journal on the same topic in the same year wasn't enough, the two teams were studying the same species: the endangered Pyrenean brown bear (*Ursus arctos pyrenaicus*). Taberlet and Bouvet mentioned that, because the entire population included fewer than a baker's dozen of individuals, capturing bears and putting them under anesthesia to study them could be dangerous for the population. Scat contains intestinal cells, and hair is often attached to follicles, so researchers can use both to obtain DNA samples. Since these two foundational papers were published, researchers have done just that, using what adds up to biological trash to investigate all kinds of important questions.

For example, one particularly long-running eDNA project focuses on the Pacific marten and fisher populations in the Sierra Nevada in California. Since the early 2000s, the U.S. Forest Service (USFS) has used baited traps to gather hair samples from these elusive mustelids. A hunk of chicken wrapped in protective wire is attached to a tree and surrounded by spiraled, blunted nails with the points pointed outward (*see the image on page 154*). The spirals of the nails grab and collect whatever fur animals leave behind while trying to get at the meat. Jody Tucker and other scientists from the USFS, along with colleagues at institutions in Montana, compared samples from current fisher populations to those from museum specimens obtained in the late 1800s. They assessed when the population's gene pool became less diverse, implying that the population underwent a severe decline in abundance (called a *genetic bottleneck*). Along with a more recent bottleneck that occurred simultaneously with intensifying European colonization of California in the late 19th to early 20th centuries, they discovered the shadow of a population decline that occurred before 1850. It is possible that this earlier decline was caused by two megadroughts that occurred before 1400, highlighting fisher sensitivity to current climate change projections.

Environmental DNA has also been used to determine whether apex predators are still present in an area, important information for their protection. In 2012 and 2013, wildlife biologist Andiara Silos Moraes de Castro Souza of the Universidade Federal de São Carlos and her colleagues in Brazil walked trails and roads, collecting scat. After analyzing the samples, they found that three jaguars were still present in the Santa Virginia unit of the Serra do Mar State Park. DNA studies of scat did what three years of camera trapping could not: confirm this apex predator's presence in the area. What's more, the use of eDNA made it possible to determine that two of these jaguars were females, which means that this tiny population will likely reproduce and grow.

Because our ability to detect and sequence DNA from smaller and smaller sources has grown—and because gene sequencing techniques have become more refined and cheaper—researchers are now moving on to more removed sources of DNA.

DNA and RNA, Everywhere

The first time I provided an unintentional sample of eDNA—though no one was actually collecting it—I was doing fieldwork in Madagascar. It was early October eight years ago, and we were hiking through a wet, rocky ravine on our way back from setting up a camera trap at a tree that locals swore was a mating place for fosa, a

catlike mammal. As I paused to rest, I removed my hat for a second, thinking I had felt a terrestrial leech inching near my ear. (Yes, a terrestrial leech. Unfortunately, the northeastern rainforests are wet enough that leeches can live outside water.) I scanned the hat, but nothing was there. I was just about to place the hat back on my head when a Malagasy field assistant, Didice, stopped me. He reached over and plucked at my hair. I turned to see him holding the fattest leech I had ever seen in my life, swollen with my blood.

My vision went black; my knees weakened. I didn't drop to the ground, but I was close. The rest of our way back to camp, I flinched and smacked at myself every 30 seconds, much to the amusement of everyone else.

Leeches like the one that bit me hold troves of genetic data about animals in the forest by virtue of their diet. By sucking on the blood of other animals, they provide nicely packaged samples for researchers to use to investigate what other species are around. Bonus: You don't have to go to them, they come to you! If anyone at that site eight years ago had been collecting *iDNA*—eDNA derived from bloodsucking invertebrates—they would've detected a human among the white-fronted brown lemurs and falanouc.

R5 Sierra Nevada Carnivore Monitoring Program, CC BY 2.0

In the Sierra Nevada in California, a marten seeks out chicken bait in a noninvasive trap that collects their fur for later DNA analysis. As the marten tries to get at the bait, blunted nails surrounding it nab fur from the animal. This long-running study began in the early 2000s and was an early adopter of eDNA methods.

In 2012, Ida Bærholm Schnell of the University of Copenhagen and her colleagues showed that iDNA works effectively for surveying wildlife in Vietnam, detecting even the Annamite striped rabbit, which was new to Western science at the time. Since then, researchers in Mozambique, Australia, China, and, yes, Madagascar, have been grinding up leeches, flies, and even copepods—the latter mistakenly termed "fish lice"—to get at their ingested DNA. Using these bloodsuckers, scientists have done everything from taking species inventories in protected areas to looking at the population structure of whale sharks.

Environmental DNA can be accurate, but it can also be extremely sensitive.

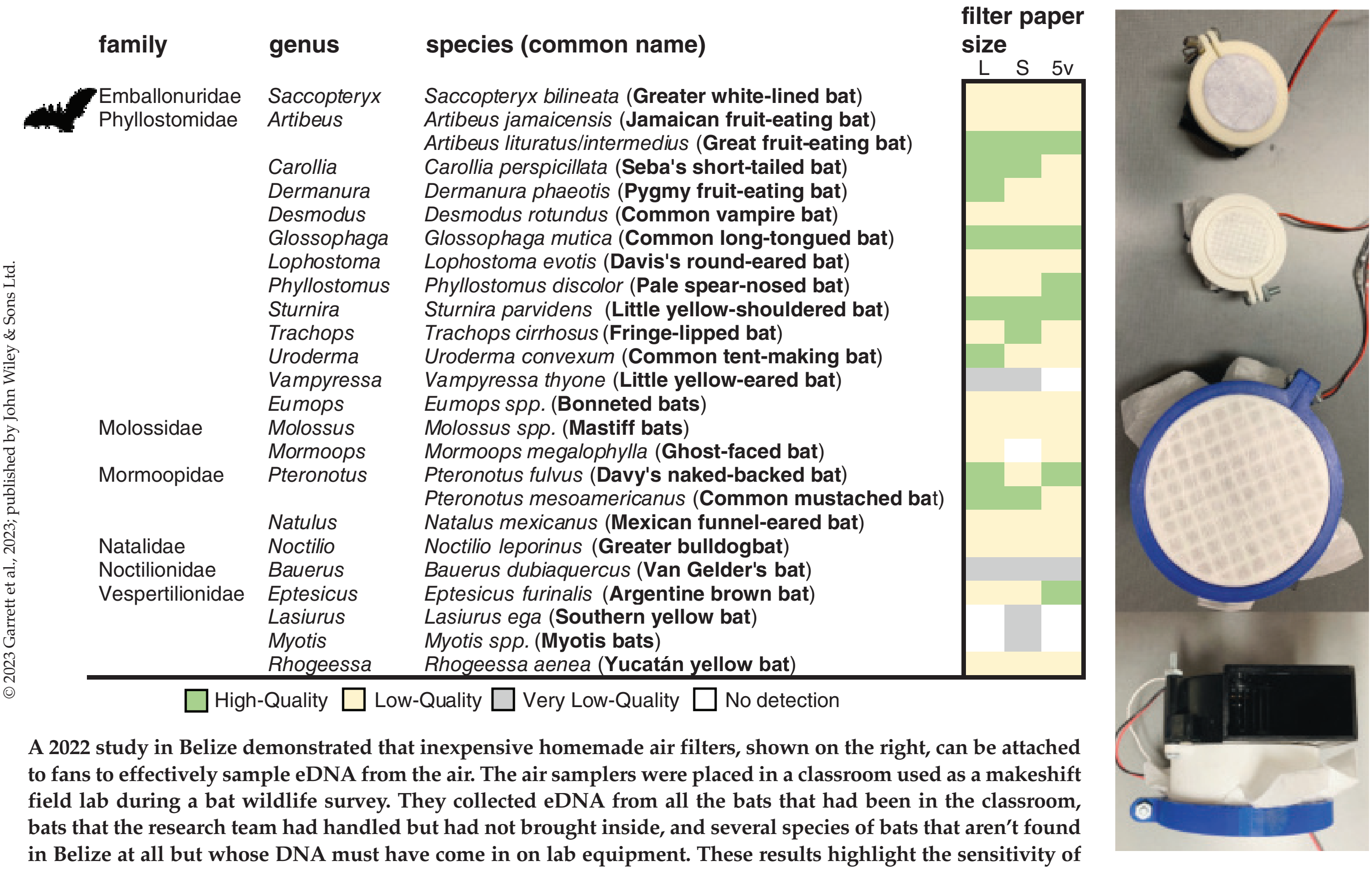
But a leech physically touches the animal a scientist wants to study; let's get even further removed. Whee-Moon Kim and colleagues at Dankook University in South Korea used stainless steel bowls filled with water to collect spit, shed skin, hair, and particles of feathers from animals that visited or passed by them. The team then identified genetic sequences using a technique called *metabarcoding*. They were able to detect 21 different species, including the Jeju striped field mouse, a species that is endemic to the island of Jejudo and that had eluded traditional field survey techniques.

What is metabarcoding?, one might ask. Think of the last time you went grocery shopping and asked a clerk whether they had a certain item. They probably scanned a barcode tag on the empty shelf, so they could look in a reference database that told them whether the item was in stock. DNA barcoding does roughly the same thing. After using PCR to amplify DNA from scat, hair, or water (as was the case for Kim and colleagues), researchers attempt to match specific sections of the DNA strand to a certain reference sequence. When researchers are focused on a specific species, such as snow leopards, they can refer to only one "barcode" sequence, which tells them if the sample they have is from a snow leopard. For the researchers from South Korea, they had multiple barcode sequences—including one that coded for the Jeju striped field mouse—which they compared to the various samples of DNA they had collected in the water. That is metabarcoding.

Garrett and her colleagues employed this same technique of scattershot matching in that classroom in Belize. First, the team set up in the classroom to take measurements from bats captured outside with a mist net. While there, the bats shed microscopic bits of fur and skin, which the air filters later picked up, allowing Garrett to detect all the bat species they had brought in the room. They also detected proboscis bats, which they had caught and released in the field, but whose DNA must have come into the classroom when they aired out the capture bags. Kinkajous and horses aren't bats, but they had been seen outside near the classroom on occasion, allowing easy cross-contamination. And the detection of other species of bats that weren't found anywhere near Belize, including the eastern small-footed bat, was likely due to eDNA traces on equipment that the scientists had used elsewhere in the world as well as in Belize.

Garrett's team's study shows two things: Environmental DNA can be accurate, but it can also be extremely sensitive. Such extreme sensitivity is a double-edged sword. On one hand, even if a species is incredibly rare and leaves little trace, it could be detectable with eDNA methods. On the other hand, if you don't know what species are likely to be present in the area, you might think that, due to cross-contamination from some seafaring adventure, there are humpback whales among the Chinook salmon in Lake Michigan. And that's not the only issue that researchers are facing when it comes to developing eDNA methods.

Researchers seeking out traces of fish DNA in streams and rivers are constantly faced with not knowing whether a detected species is present at the sampling site or 20 kilometers upstream. Because eDNA is incredibly stable and can be present in an environment for up to thousands of years—think the Arctic permafrost—researchers must contend with not knowing whether the species



A 2022 study in Belize demonstrated that inexpensive homemade air filters, shown on the right, can be attached to fans to effectively sample eDNA from the air. The air samplers were placed in a classroom used as a makeshift field lab during a bat wildlife survey. They collected eDNA from all the bats that had been in the classroom, bats that the research team had handled but had not brought inside, and several species of bats that aren't found in Belize at all but whose DNA must have come in on lab equipment. These results highlight the sensitivity of eDNA and the potential for cross-contamination when using these methods.

they detected was present in an area yesterday or weeks ago. Dead bodies shed eDNA just as well as living bodies.

The Cusp of the eRNA Revolution

To avoid the cons of eDNA, Matthew Yates and colleagues at the Université du Québec à Montréal and McGill University suggest the use of *eRNA*. Unlike DNA, RNA is more actively involved in protein expression, which happens only in living organisms, and it degrades much faster. This rapid degradation is bad if you can't analyze samples quickly, but it's great when you want a snapshot of what species are present *right then* in an area. As Yates and his colleagues described in a 2021 review, organisms that might have similar eDNA profiles can exhibit differences in their eRNA, due to stress, age, or sex, all characteristics that researchers love to know about. The use of eRNA—at least when it comes to water and air samples—is still in its infancy compared to eDNA, largely because of how quickly it degrades. But it's sure to become a force in the field.

Even if researchers begin incorporating eRNA into eDNA surveys, they will still face another challenge. Nobody has yet figured out how to turn eDNA samples into meaningful abundance or density estimates, despite studies showing eDNA concentration is positively correlated with abundance in some situations. That information is more useful than knowing merely whether a species is present, stressed out or no. Traditional survey methods, such as camera traps or actual capture, often remain more efficient or effective than eDNA for such population studies. Traditional methods may also be better because genetic reference libraries may lack the sample sequences necessary for researchers to match field samples to the correct species—which is what happened in Madagascar for PhD candidate Mai Fahmy of Fordham University and her colleagues—or because for some mysterious reason some animals elude detection via genetics but not via camera trap.

In short, eDNA techniques are still in development. But that uncertainty is one reason why they are so exciting. Whether we will one day be able to effectively monitor wildlife populations merely by scooping up air samples, or whether eDNA simply becomes another noninvasive tool in our ever-expanding toolbox, the future of turning biological trash into treasure is bright.

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Why STEM Education—and Democracy—Need Civic Science

Science and technology programs should prepare students for public engagement.

Christian H. Ross and Samantha Jo Fried

Sigma Xi and the *Journal of Science Policy and Governance* (*JSPG;* sciencepolicyjournal.org) released a special issue in May 2022 on STEM education and workforce development. In this series, authors from the special issue discuss findings from their work.

The effects of science and technology extend far beyond the confines of the laboratory. "Perhaps never before in living memory have the connections between our scientific world and our social world been quite so stark as they are today," said former deputy director of the White House Office of Science and Technology Alondra Nelson in her 2021 Biden Science Team nomination speech. She elaborated, "Science at its core is a social phenomenon. It is a reflection of people, of our relationships, and of our institutions." Indeed, science is a social enterprise, one that helps us address critical societal questions, such as how can we build communities resilient to climate change and extreme weather, what public health measures do we need to respond to health threats, and how can we promote responsible innovations in artificial intelligence in the workplace. Science and technology are essential and inescapable aspects of our shared civic lives. Democracy, therefore, needs engaged and informed civic participants who understand science and technology and the roles these disciplines play in society.

Since the release of Vannevar Bush's landmark report to President Truman, *Science—The Endless Frontier,* in 1945, the United States government has continued to emphasize as a national priority the training of more scientists and technologists to equip our country to respond to the challenges of the future. To that end, the Obama administration announced in 2012 that increasing the number of STEM graduates by one million students by 2022 would be a priority across all government agencies. And although the United States continues to graduate more STEM degree–earners each year, the United States Census Bureau's 2019 American Community Survey reported that more than two-thirds of STEM graduates do not end up in a STEM career—a pattern that has intensified over the past decade. Most new STEM graduates will not shape science and technology in a research lab or at the next Silicon Valley start-up; nor will they serve as an expert science advisor. Rather, whatever their professions, these highly trained individuals will apply their understanding of science and technology in countless personal and everyday ways, including their decisions about what to buy at the supermarket, the questions they ask at the doctor's office, the way they educate themselves and their children, the opinions they post on social media, the discussions they have with friends and family, and the way they vote at the ballot box.

More than two-thirds of STEM graduates do not end up in a STEM career—a pattern that has intensified over the past decade.

Despite this growing reality for STEM graduates, many STEM programs still do not adequately prepare graduates to apply their technical training broadly, communicate their scientific understanding widely, or engage with societal matters. STEM education in the United States must do more to prepare the next generation of STEM-trained civic participants, not just the next generation of scientists and technologists. We propose *civic science education* as a way to better prepare the abundance of

QUICK TAKE

STEM graduates have a responsibility to use their knowledge for civic good, regardless of whether they pursue careers in the sciences.

Currently, most STEM programs do not prepare students to apply their education to societal challenges outside of the academy.

Civic science teaches STEM students how to place science in context, communicate science more effectively, and engage in civic participation.

Alonso Nichols/Tufts University

Kyrielle Lord, an engineering major and a Tisch Scholar at Tufts University, engaged with the local community in summer 2022 by working with the Mystic River Watershed Association to remove the European water chestnut, an introduced species.

STEM graduates for their roles and responsibilities in society.

What Is Civic Science?

Civic science is a growing, multidisciplinary field of research and practice that approaches scientific and civic issues as fundamentally intertwined. It emphasizes the importance of understanding science in context and engaging with diverse communities to create equitable and democratic solutions to societal problems. Scholar and practitioner of civic engagement Peter Levine, who is the Lincoln Filene Professor of Citizenship and Public Affairs in the Jonathan M. Tisch College of Civic Life at Tufts University in Massachusetts, argues that the precise meaning of "civic" changes based on context, ranging from matters of political power and personal virtue to the commons and community building. We advocate for an expansive definition for the "civic" in civic science: We suggest that whenever people who have trained in STEM disciplines engage with societal issues related to science and technology for the purpose of advancing the public good, they are also engaging in civic science.

STEM training equips students with powerful intellectual and practical skills that come with a corollary set of civic responsibilities to engage with the social and political issues related to their scientific expertise. Civic science education as part of undergraduate STEM training prepares students to fulfill those responsibilities by teaching them ways to apply three essential skills: understanding science in context, communicating science effectively, and engaging actively in civic issues.

Understanding Science in Context

First, civic science education trains STEM students to recognize how scientific knowledge and technological innovations are situated within broader societal contexts. Contexts are a bit like Russian nesting dolls: The more closely you examine them, the more you find that they contain many additional and often varied, related contexts. For instance, a student might start with the assertion that the Earth's climate is warming. They might then ask questions such as these: What data do scientists have to support this claim? How do scientists know to look at long-term temperature patterns, sea surface temperatures, melting ice, and deforestation (among other things) when they consider a changing climate? Who are the scientists conducting this research and why should we believe them? What institutions provide the funding to make these studies possible? Whom does a changing climate affect and how? Why should we care?

There is context nested within every assertion, scientific and otherwise. An understanding of the broader contexts makes scientific knowledge more specific, more meaningful, and more personal. Understanding these broader contexts is essential for solving societal problems. Although STEM expertise is certainly indispensable, it is just one of multiple kinds of expertise across a diversity of disciplines, communities, and experiences that are all necessary for members of a society to work together toward more complete and equitable solutions. Civic science education prepares STEM students to approach science and technology not only as technical matters but also as social and political matters that reflect societal values and priorities. Scientific institutions, practices, and even scientific findings are all influenced by these contexts.

Effective Science Communication

Second, civic science education teaches STEM students that effective science communication requires more than facts alone. Civic science practitioners must understand their target audience and be able to articulate how their values and those of their audience are an integral part of the broader scientific message. Students learn to ask questions that will help them make a better connection: Who am I communicating with? What do they care about? How might this scientific topic affect them? Approaching these questions thoughtfully requires a degree of self-reflective awareness about one's own position and how one's message may be perceived. Civic science education prompts STEM students to reflect on how their own values, experiences, and assumptions shape their understanding of scientific and technological topics, as well as how those perspectives may meaningfully differ from the perspectives of others.

STEM training equips students with powerful intellectual and practical skills that come with a corollary set of civic responsibilities.

Although science communication is important at all levels of society, for most STEM graduates, their primary audiences will likely be people with whom they already have relationships: their family, friends, and close communities. To be effective science communicators, STEM students must learn to empathize with (or at least understand) others' motivations and concerns. By making personal and relational connections with others, they can more easily understand how their scientific message is important and relevant to those around them.

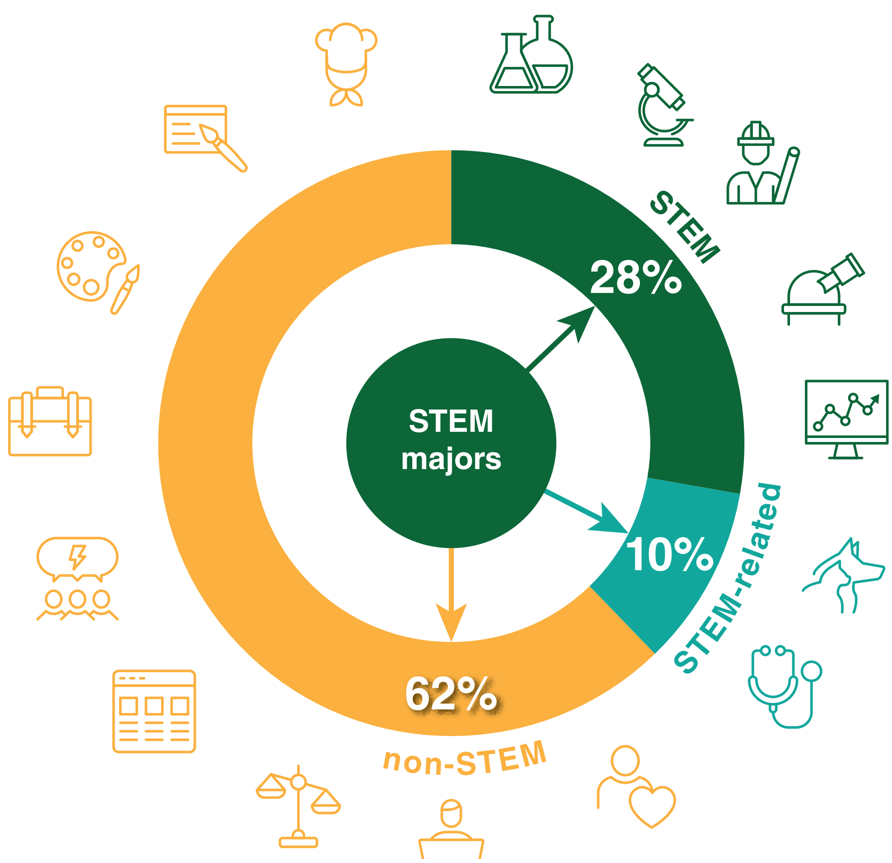
Good science communication also takes into account one's own tone, perceived affiliations or attitudes, and background assumptions in order to shape the scientific message in a way that minimizes opportunities for miscommunication or conversational impasse. Importantly, if science communication comes across as dismissive or condescending, then it may very well not be taken seriously, no matter how accurate or important the underlying ideas might be. Connecting with some audiences can be challenging, especially when there are areas of deep disagreement. But civic science helps to develop the essential skill of connecting values and relationships with science and technology issues.

Enhanced Civic Engagement

Third, because of their training, STEM students have the distinct responsibility to help answer technical questions, as well as civic questions, about the most constructive ways to understand, create, and use science and technology in our world. Civic science education provides STEM students with the experiences and tools to fulfill those responsibilities. In a 2021 study, researchers at the State University of New York at Albany examined common civic science educational practices in the United States, including exposure to the intersection of societal and scientific issues, enrollment in citizen science projects, and participation in science-oriented civic action. They found that civic science education helped students better understand both scientific and civic topics, such as how legislation works, how policies are made, and how budgets are set. The researchers also found that incorporating civic science into STEM education helps students connect their technical training with personal values and increases their level of civic engagement.

Civic engagement from STEM graduates is essential for a healthy democracy because, despite the temptation to treat the value of science as self-evident, science does not, in fact, speak for itself. Society needs civic participants who understand how science works and who recognize its value in informing decision-making that affects peoples' lives and our world. Enhancing civic engagement among STEM students is

Current Professions of College Graduates Who Majored in STEM Fields



Barbara Aulicino; icons by Dilyaab/Shutterstock

Undergraduate STEM majors enter a wide variety of professions—most of which lie outside of science and technology, according to the United States Census Bureau's 2019 American Community Survey. (Data from Cheeseman Day and Martinez, 2021.)

not a static, one-and-done achievement. It is a continual process of learning by doing and of trial and error. It is a lifelong commitment to taking seriously the responsibility to engage with the technical and civic dimensions of science and technology and the human values inherent in them.

Civic Science in Practice

Incorporating civic science into undergraduate STEM education can take many different forms. Since 2016, Tufts University has offered one of the few co-major programs that enable students to practice their scientific disciplines with both technical and civic rigor. As co-majors, students enhance their STEM training by pairing it with concurrent training in civic studies and science and technology studies (STS). They take courses in the humanities and social sciences that specifically complement their technical science training, including anthropology courses such as "Introduction to the Anthropology of Science and Technology" and sociology courses such as "Sociology of Science and Risk and Epidemics: Plagues, Peoples, and Politics." Co-majoring STEM students also take STEM courses that include a focus on civic issues, such as the biology course "Food for All: Ecology, Technology, and Sustainability" and the computer science course "Cyberlaw and Cyberpolicy."

Civic science provides an opportunity to reimagine the purpose of STEM education as practical training for the next generation of civic participants.

Civic science education can also come in the form of interdisciplinary research labs that train STEM undergraduates to simultaneously engage with technical skills, civic contexts, and personal values. The Digital Humanities Lab at Emory University in Georgia operates in this mode. Led by Lauren Klein, a professor of English and of quantitative theory and methods, the Lab teaches computer science students to incorporate humanities principles into data science practices by engaging with the history of data visualization techniques and with concepts of data justice to inform their technical training as technologists. The Civic Laboratory for Environmental Action Research (CLEAR) at Memorial University of Newfoundland in Canada follows a similar approach. CLEAR is led by Max Liboiron, a geography professor, who trains students to study environmental issues as scientists who are explicitly feminist and anticolonial. Students learn about the inherently political nature of creating knowledge, and how knowledge can reproduce specific kinds of values and interests.

Courtesy of Max Liboiron/CLEAR

Liz Pijogge (*right*), the Northern Contaminants Researcher for the Nunatsiavut Government, and Joseph Onalik (*left*), a research technician at the Nunatsiavut Research Centre and Memorial University, prepared a flow meter for microplastics monitoring with the CLEAR lab in St. John's, in the Canadian province of Newfoundland and Labrador, in 2022. Pijogge live streamed the event over Facebook so people in Nunatsiavut (the Inuit land claim area in Labrador, Canada) could watch.

Integrating civic science more fully into higher education will require sustained effort and investment on the part of universities. The best approaches to accomplish this goal will likely vary across contexts. For example, larger, research-heavy universities may leverage their research infrastructure to provide students with opportunities to connect STEM research experiences with research centers or community partners who are addressing civic problems. Smaller liberal arts colleges may develop new degree programs or concentrations that integrate civic science education into courses designed and co-taught by faculty from both STEM and humanities disciplines.

Regardless of the specific setting, civic science education is important in preparing STEM students for their civic roles and the responsibilities they have by virtue of their scientific and technological training. Civic science provides an opportunity to reimagine the purpose of STEM education, not only as a functional pipeline for the future scientific and technical workforce, but as practical training for the next generation of civic participants.

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Relativity and the World of Molecules

Einstein's revolutionary theory, merged with quantum mechanics by Dirac, permeates chemistry and helps us understand the behavior of heavy elements.

Abhik Ghosh and Kenneth Ruud

Mention Albert Einstein's theory of relativity to people and it commonly conjures up a sci-fi world of time travel and black holes. Relativity also plays a critical, if somewhat less widely known, role in many real-world devices that define modern life—cell phones, TVs, and GPS devices. However, in chemistry—the world of molecules, materials, medicines, and their transformations—relativity is scarcely ever mentioned, especially at the introductory level. Indeed, the word is likely to draw blank stares even among professional chemists. Some well-informed chemists would perhaps point out that the unique color of gold and the liquidity of mercury are manifestations of relativity. A handful may even recall media reports that lead-acid batteries derive some 80 percent of their power from relativistic effects.

But for both of us, relativity is our bread and butter. Relativistic effects are everywhere in the equations we use to calculate molecular properties, and in the computer codes needed to solve those equations. As we synthesize novel molecules in our laboratory, such calculations help us interpret and harness their properties, and are part of our efforts to develop diagnostic and therapeutic agents for cancer. That "sci-fi world" that Einstein opened up a century ago now serves as a profound creative force in our research.

Relativity enters chemistry primarily through its effects on the electronic structure of atoms and molecules. Because the masses of electrons and nuclei are tiny, the general theory of relativity, which is concerned with gravitation and its relationship with physical laws, is of no concern to us. Instead, it is the effects of the special theory of relativity—special here referring to the absence of gravity—that affects chemistry. In heavy elements—especially those in the bottom two rows of the periodic table—electrons attain such high velocities that special relativity cannot be ignored. Einstein's theory predicts that these electrons will increase in apparent mass, what we call a *scalar relativistic effect*. This effect is caused purely by relativity theory, with no real contribution from quantum mechanics.

Much more interesting, and omnipresent in heavy-metal chemistry, are *spin–orbit effects*, which are an offspring of both relativity and quantum mechanics. These effects have to do with a phenomenon called *electron spin*, which is often jokingly referred to as "the spin of a particle, except that it is not spinning, and it is not a particle." That may sound like a Zen koan, but we assure you that it is completely true. An electron is a hybrid entity that sometimes manifests as a particle and sometimes as a wave. As a wave, it does not rotate but nevertheless has an attribute called *spin*, which causes it to respond to magnetic fields as if it were a rotating charged particle.

Electron spin is a consequence of merging special relativity with quantum mechanics, so every spin effect is also a relativistic effect. Although the physical nature of electron spin is esoteric, its effects are familiar all around us: from glow-in-the-dark materials on T-shirts and children's holiday costumes all the way to auroras in the upper atmosphere. Our favorite challenge right now is figuring out how to interpret and apply the theory of electron spin in the context of atoms and molecules. We are even trying to exploit spin effects in heavy element compounds for photodynamic therapy, a type of treatment for cancer and increasingly for microbial diseases.

Chemistry at High Speeds

Most of our research and much of modern chemistry focuses on *transition metals*, the rectangular block of elements sandwiched between the *alkali* and *alkaline earth metals* and the so-called *main-group elements* in the periodic table (*see figure on page 162*). The transition metals are grouped into four horizontal segments in the fourth to seventh rows, called *periods*, of the periodic table. In particular, those metals in the fourth to sixth periods play an outsize role in chemistry and indeed civilization, used for everything from tools and machinery to industrial catalysts to coinage.

Within any given vertical column of the periodic table, the uppermost or lightest transition metal (in period 4 of the periodic table) is invariably

QUICK TAKE

Relativity was long thought to be largely a subject of interest to physicists, and inconsequential to the processes underlying chemical phenomena and reactions.

Relativity is now recognized as a major factor underlying chemical differences between elements in periods 5 and 6 of the periodic table.

Exploiting relativistic effects is leading to improved reagents, catalysts, and medical-imaging and therapeutic agents involving heavier elements.

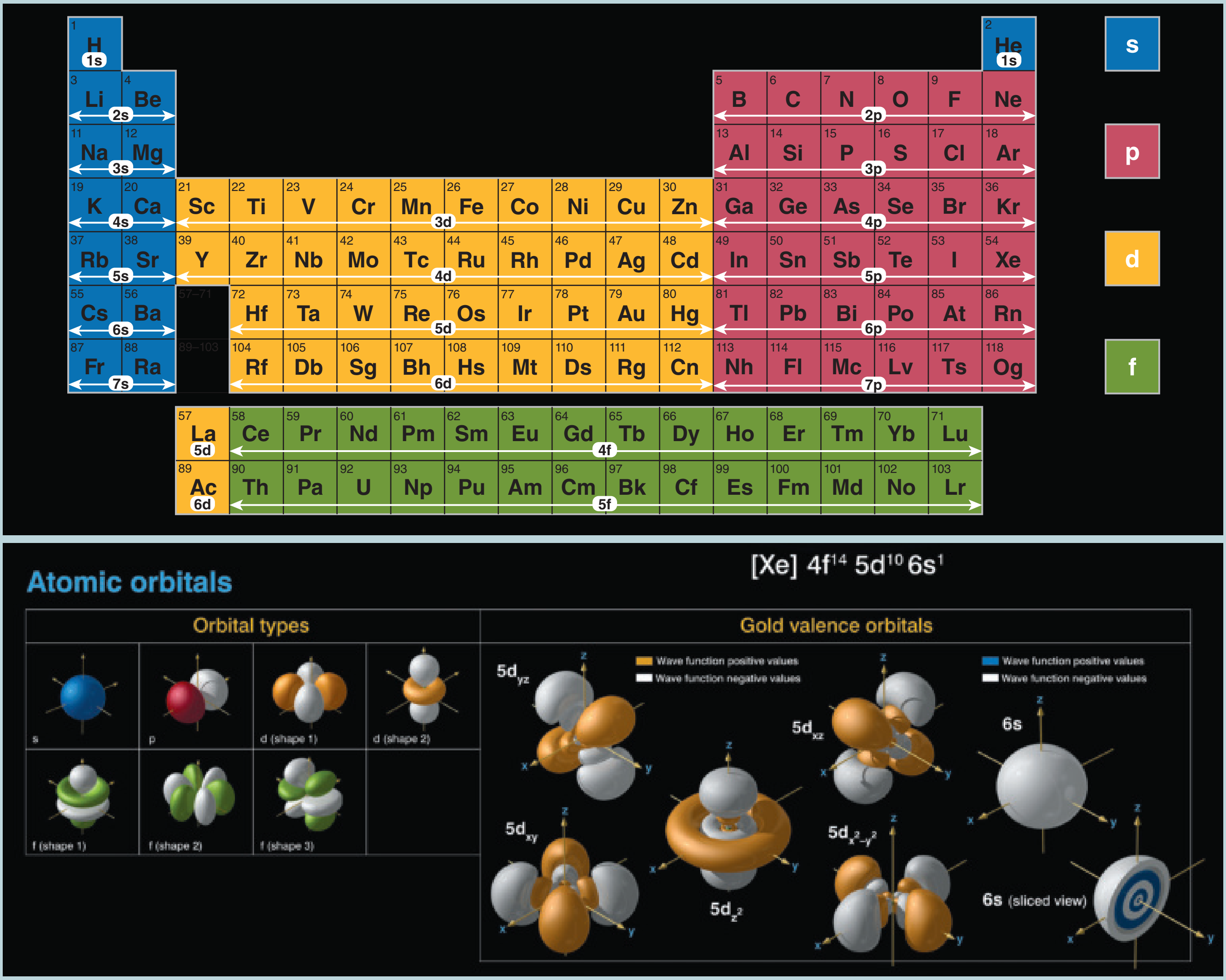
BlueOrange Studio/Shutterstock

The aurora borealis, or northern lights, illuminates the sky above Tromsø, Norway, the authors' home city. The glow in part comes from the phosphorescence of atoms and molecules in the upper atmosphere, a physical process that can be explained using a combination of relativity theory and quantum physics. Although relativity is usually connected only with physics, it also affects many aspects of chemistry that are all around us.

chemically unique, whereas the next two metals (in periods 5 and 6) are chemically much more similar to each other. "Much more similar" does not, however, mean identical. Far from it! Historically, chemists have ascribed these variations to the difference in the number of electrons between the two rows. However, by comparing full relativistic computations with computations in a fictitious simulated world that doesn't have relativistic effects, we have come to realize that these differences are largely because of special relativity, specifically the much greater impact of relativistic effects on period 6 metals relative to those in period 5 of the periodic table. This awareness serves as a potent creative force for us and, we hope, for other inorganic chemists as well, allowing them to zoom in on the optimum reagent or catalyst that they need for a given chemical transformation.

Einstein published his special theory of relativity in 1905 at a time of momentous change in physics, when physicists were also beginning to understand the quantum nature of matter. Relativity addresses particles traveling at velocities close to that of the speed of light in vacuum, which according to Einstein's theory is constant and independent of the frame of reference. This last statement is a good deal more remarkable than it appears. For instance, if you are "chasing" a light particle at nine-tenths of the speed of light, you will still see it moving away from you—not at one-tenth of the speed of light, but at the *full* speed of light. To explain this apparent paradox, Einstein had to propose some other phenomena that also seem paradoxical but that have since been confirmed by experiment: A clock moving close to the speed of light runs slower, a ruler gets shorter, and a barbell becomes more massive, as measured by an external observer. These are the consequences of relativity.

In particular, the last two effects are important for chemistry. For instance, the electrons closest to the nucleus—the 1s electrons—in a mercury atom move at nearly 60 percent of the speed of light. Because of the effects of spe-



Abhik Ghosh and Kenneth Ruud, adapted by Barbara Aulicino; Carlos Clarivan/Science Source

The shape of the periodic table is controlled by the underlying structure of electron orbitals (labeled 1s–7s, 2p–7p, 3d–6d, and 4f–5f). Top: Elements are grouped according to their outermost orbitals that are occupied by electrons. Yellow elements are the *transition metals*, and relativistic effects can greatly affect the energy of the outermost d orbitals of these elements. Bottom: The shapes of orbitals describe where an electron is most likely to be found at any moment. *Valence electrons* are those that are free to participate in chemical bonding and reactions—typically the outermost electrons. In gold atoms (Au, element 79), these include 10 electrons in the 5d orbitals and one electron in the 6s orbital. (The nonvalence or core electrons of gold have the same arrangement as a xenon atom, as indicated by the symbol [Xe].) The color of gold reflects relativistic effects on the valence electrons in this element's atoms.

cial relativity, their apparent mass increases by about 55 percent, and the orbital they travel in contracts by about 23 percent. Indeed, all of the s orbitals contract, and so do the p orbitals. (All elements below the first row of the periodic table have one s orbital and three p orbitals in each electron shell, which are filled by two and six electrons, respectively.) In transition metals such as mercury, the contraction of the s and p orbitals results in more efficient "screening" of the nuclear charge from the electrons in the remaining orbitals, called the d and f orbitals, which expand as a result.

A very tangible consequence of these scalar relativistic effects is an increased binding energy of s and p electrons, and a decreased binding energy of d and f electrons. These effects are accentuated as we go down in the periodic table. Although we generally expect the reactivity of the alkali metals to increase as we go down in the periodic table because the outermost electrons are held less tightly by the nucleus (as quantifiable, for instance, by the lowering of the energies needed to ionize the atoms), relativity increasingly stabilizes the outermost occupied s orbital, so that the ionization energy of francium (element 87) is *higher* than that of cesium (element 55)! The relativistic contraction of s orbitals also makes it harder for mercury (element 80) to engage in strong interatomic interactions: Relativity thus explains why mercury is a liquid, not a solid, at room temperature. Although this qualitative explanation has been known for a long time, it should be noted that extensive computer calculations were necessary to verify that relativistic effects truly are responsible for mercury's relatively low melting point. And there are several other, more recently discovered examples of the relativistic effects on d and f orbitals.

Unexpected Couplings

Spin–orbit interactions are the other manifestation of relativity on the electronic structure of atoms and molecules. To understand these inter-

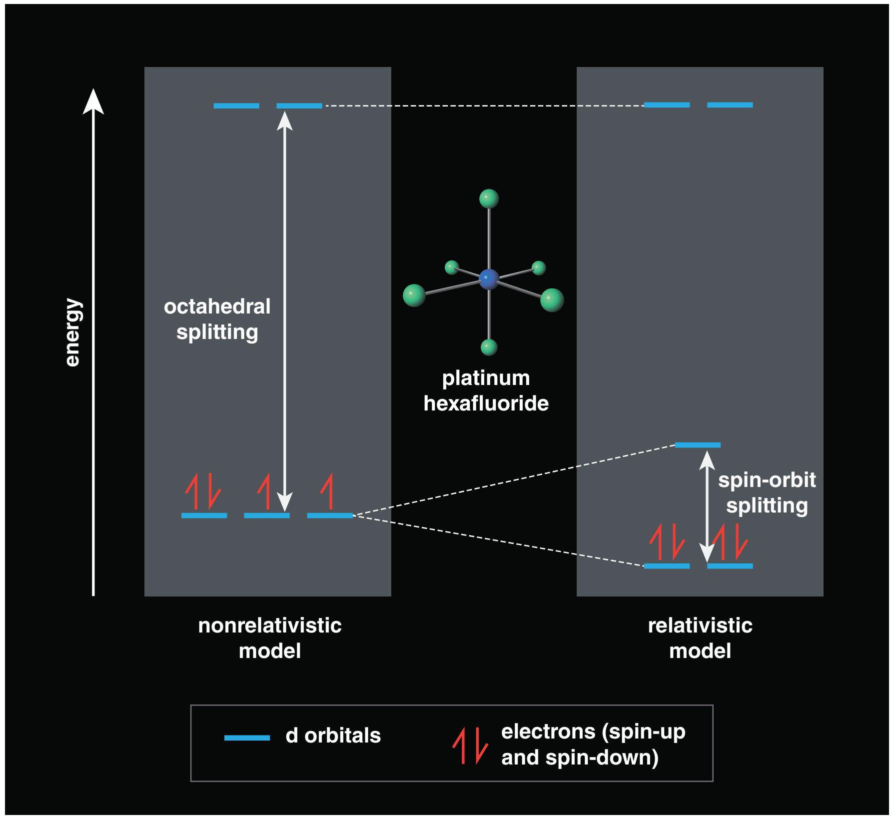
actions, we have to dig deeper into the revolutionary discoveries of physicists in the early 20th century.

In 1926, Erwin Schrödinger formulated an equation that described how particles (now interpreted as quantum wave functions) respond to external fields. In effect, he updated Newton's second law to the language of quantum mechanics. But by solving one problem, Schrödinger created another: His theory did not satisfy Einstein's theory of special relativity. For example, it did not have the proper invariance under changes of reference frame. Perhaps more damningly, under certain circumstances, a particle has a nonzero probability of traveling faster than light and traveling backwards in time. In Einstein's theory of special relativity (contrary to science fiction), neither of these is possible.

Two years later, Paul Adrien Maurice Dirac reconciled quantum mechanics with relativity, deriving an equation of motion for the electron that fully satisfies the invariance properties required by Einstein's theory. In doing so, he predicted the existence of the *positron*, a particle with the mass of an electron but a positive instead of negative charge, and he was able to account for some surprising experimental observations made by German physicists Otto Stern and Walther Gerlach in 1922 on the splitting of beams of silver atoms.

Like its soft-spoken inventor, Dirac's equation is easy to underrate, compared with more famous physical laws such as Schrödinger's equation or Einstein's iconic $E = mc^2$. In fact, it is a more subtle version of both of these equations. Indeed, Dirac himself underestimated the importance of relativity and his equation for chemistry: "These [relativistic effects] give rise to difficulties only when high-speed particles are involved, and are therefore of no importance in the consideration of atomic and molecular structure and ordinary chemical reactions."

For chemists, the Schrödinger equation prescribes the allowed states of an electron and provides the theoretical basis for orbitals, explaining why there is one s orbital, three p orbitals, and so on. But as a nonrelativistic theory, it is incomplete. Dirac's equation adds relativity into the picture. It tells us that every electron, whether it is in an atom or not, has an additional property called spin, which takes on values of half a quantum of angular momentum.



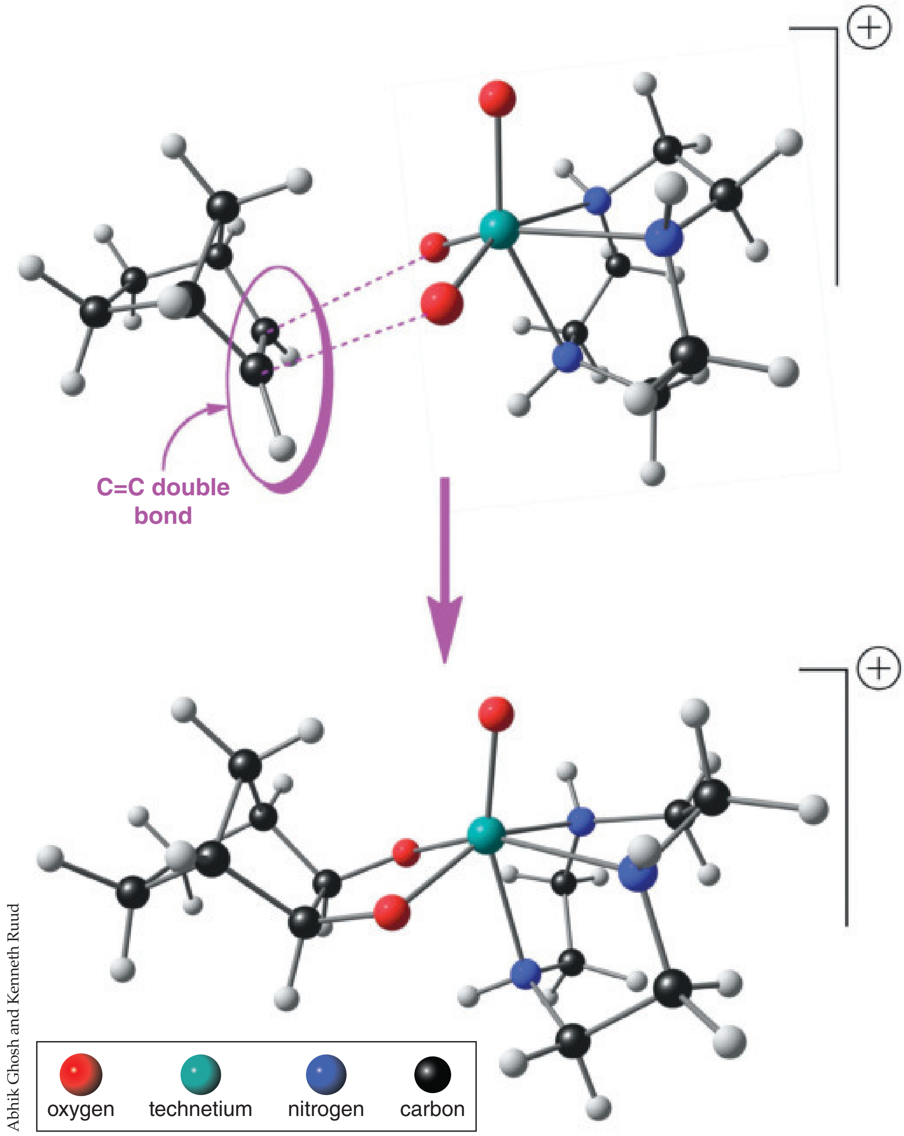
Abhik Ghosh and Kenneth Ruud, Dana Mackenzie, Barbara Aulicino

The molecule platinum hexafluoride (PtF_6) illustrates some of the subtle effects of relativity on chemistry. In a nonrelativistic model (*left*), four valence electrons are distributed among three lowest-energy d orbitals, leaving two electrons unpaired. In a relativistic model (*right*), these three orbitals undergo a further split in energy. The four electrons congregate into the lowest two levels, leaving no electrons unpaired, with implications for the molecule's magnetism and reactivity.

This part of our story requires precision. Remember that quantum mechanics is based on the idea that every observable property is *quantized*, meaning it comes in integral multiples of some fundamental value. Angular momentum is one such property, as is its component along a given axis. According to the Schrödinger equation, an electron in an atom will always have an angular momentum that is a whole number l, called its *orbital angular quantum number*, and for the component of the angular momentum along the z axis there is also a whole number m_l, called its *azimuthal quantum number*. For an electron in the s orbital, the angular momentum $l = 0$. For an electron in the p orbital, $l = 1$ and the value of m_l can be −1, 0, or 1. For an electron in the d orbital, $l = 2$ and m_l can equal −2, −1, 0, 1, or 2, and so on.

The relativistic contraction of s orbitals makes it harder for mercury to engage in strong interatomic interactions, which explains why mercury is a liquid, not a solid, at room temperature.

But Dirac's correction to the Schrödinger equation tells us that each electron contributes a half-quantum of angular momentum (or spin), its *spin*



A double bond in an organic molecule (*top left*) bonds with a radioactive technetium ion (*top right*) to form an organotechnetium molecule, illustrating a potential methodology for synthesizing tracers for medical imaging. It's reasonable to expect that one could potentially optimize the process by replacing radioactive technetium (element 43) with its heavier, nonradioactive sibling rhenium (element 75), located just below it on the periodic table. As a result of much stronger relativistic effects in rhenium, however, the analogous reaction does not work with rhenium. Researchers are therefore obliged to do all the optimization experiments with technetium isotopes.

quantum number. The electron spin can be either oriented along or opposed to the direction of the orbital angular momentum. In an orbital, you can have at most two electrons, one along and one opposed to the direction of the orbital angular momentum.

But the Dirac equation goes further and couples the orbital angular momentum to the spin. The total angular momentum j will then be either $j=l+½$ or $j=l-½$, and these states will now have different energies. But because of this coupling, we can no longer talk about the electron spin by itself, nor a spatial orbital by itself. Instead, it is the coupled, total angular momentum of the electron j that is quantized, and it always takes a half-integral value. This merger of the electron spin and its orbital angular momentum is called *spin–orbit coupling*.

As a result of this coupling, the three spatial p orbitals will split into a single $p_{1/2}$ (with angular momenta components along the z axis of $j_z=½$ and $-½$ corresponding to the two possible couplings of spin and angular momentum) and two $p_{3/2}$ orbitals of equal energy (with angular momenta components along the z axis of $j_z=3/2$, ½, –½, and $-3/2$). Thus, there are six quantum states available for electrons in the p orbitals, and this effect is why every row of the periodic table (after the first) has six p elements, in which one, two, three, four, five, or six of those states are filled. Likewise, the five spatial d orbitals split into two degenerate $d_{3/2}$ and three degenerate $d_{5/2}$ orbitals, which is why the d block (the transition metals) has 10 columns.

From there, the consequences of spin–orbit coupling become even more complicated. For example, when we bind a heavier transition metal (with strong spin–orbit coupling) to a lighter element, the d-electron occupancy may differ qualitatively from that expected from simple considerations of chemical binding. The octahedral molecule platinum hexafluoride illustrates this point well (*see figure on page 163*). Simple bonding considerations suggest that the four outermost d electrons distributed over three low-energy d orbitals would leave two electrons unpaired. However, spin–orbit coupling further splits the three d orbitals into a 2:1 pattern, with the four d electrons feeding into the two lowest orbitals, leaving no unpaired electrons. Unpaired electrons are more easily available for chemical bonding than paired electrons, which means that the molecule platinum hexafluoride is more stable than we would expect if there were no spin–orbit coupling.

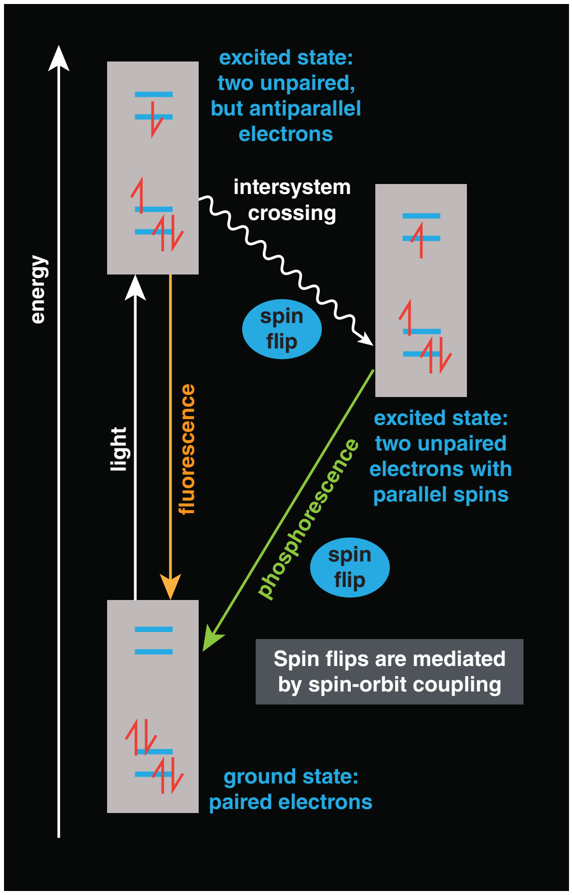
Heavy Metals

Relativity manifests itself throughout the periodic table. We can, for instance, interpret relativistic effects to understand the difference in color between silver (in period 5) and gold (just below it, in period 6). The lowest absorption band in silver and gold corresponds to photons that excite electrons from the 4d/5d energy levels to the 5s/6s energy levels, respectively. In silver, the photons that drive this transition are in the ultraviolet region (with an energy of approximately 3.7 electron volts), which is why silver does not absorb visible light; it reflects all wavelengths in an equal and, yes, silvery way. For gold, however, the relativistic stabilization of the 6s orbital and the destabilization and a larger spin–orbit splitting of the 5d orbitals lowers the absorption energy to approximately 2.4 electron volts. This energy corresponds to wavelengths in the blue part of the vis-

ible spectrum, which accounts for the distinctive golden color of the reflected light.

Relativistic effects are particularly notable in the chemistry of elements in the sixth period, such as gold. As mentioned earlier, their outermost d electrons are significantly more easily removed than those of fifth period metals. Because oxidation is nothing but removal of one or more electrons, sixth-period metal compounds are easier to oxidize than analogous metals just above them in the fifth period. The same argument holds in reverse for reduction, the addition of electrons: Compounds of sixth-period metals are harder to reduce than those of fifth-period metals. We can quantify these differences via so-called *redox potentials*, which are determined with simple benchtop equipment.

The chemistry of technetium and rhenium provides a fascinating case study of relativistic effects that have implications for nuclear medicine, the use of radioactive isotopes for imaging the body or for other medical imaging (*see figure on page 164*). Technetium (element 43), in period 5, happens to be the lightest element for which all known isotopes are radioactive. The short-lived metastable isotope of technetium (called ^{99m}Tc) is the most widely used radioisotope in medical imaging, involved annually in tens of millions of diagnostic procedures worldwide. The imaging happens via gamma rays emitted by ^{99m}Tc.



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Fluorescence and phosphorescence are two major types of light emission by molecules and solid materials. When an atom's or molecule's electrons are excited from their ground state, they can immediately return and emit a photon in the process, making the material fluoresce. Alternatively, through a relativistic effect called spin–orbit coupling, the excited electron can undergo two successive spin flips. The process is more time-consuming, and the delayed emission of a photon in the last step makes the molecule glow in the dark, or phosphoresce.

Relativistic effects on the electron orbitals of gold lower the absorption energy into the visible range, which accounts for gold's distinctive yellowish color.

The great majority of ^{99m}Tc is used in the form of a *tracer*, a molecule that carries the isotope to the specific location in the body where it will be imaged through its gamma-ray emission. It is in the design of tracers that a good understanding of technetium's chemistry becomes important. However, because ^{99m}Tc has a half-life of just six hours, researchers typically study the fundamental chemistry of technetium using a much longer-lived isotope. An even more convenient approach is to map out the chemistry with a nonradioactive element in the same column of the periodic table—specifically rhenium (Re), which sits just below technetium in the sixth row of the periodic table. Both elements exhibit highly oxidized states, such as in the pertechnetate (TcO_4^-) and perrhenate (ReO_4^-) ions. These states are called *heptavalent*, meaning that the technetium (or rhenium) atom is using seven electrons for bonding.

Heptavalent technetium, however, is more easily reduced (that is, accepts electrons) than heptavalent rhenium, because of the weaker destabilizing effect of relativity on the outermost d orbitals. The difference creates opportunities for synthesizing technetium compounds that have no rhenium analog. In the figure shown on page 164, the reducing agent is a double-bond-containing organic compound, which reduces the technetium to a pentavalent state. The resulting organotechnetium compound, or one very like it, could be potentially deployed as a tracer. Here then we have an example of technetium-specific chemistry: The much greater relativistic destabilization of rhenium's d orbitals makes the chemistry unworkable for rhenium. Indeed, a good chunk of current research on the development of ^{99m}Tc tracers, notably by Swiss chemist Roger Alberto, can be better appreciated in light of relativistic effects.

Relativity at Work

The heaviest main-group elements (the red block in the periodic table) exhibit a fascinating relativity-mediated phenomenon called the *inert pair effect*. These elements exhibit a strong preference for a lower valence than expected based on their group number in the periodic table. The phenomenon can be traced to the relativistic stabilization of the outermost s orbitals, which renders them relatively inaccessible to bonding. Thus, thallium, lead, and bismuth (Tl, Pb, and Bi, elements 81, 82, and 83, respectively) are expected to prefer valences of 3, 4, and 5 based on their positions in the periodic table, but actually prefer valences of 1, 2, and 3. The higher-valent states do exist but are strong oxidizing agents, with a strong predilec-

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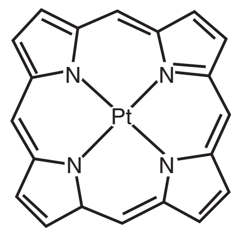
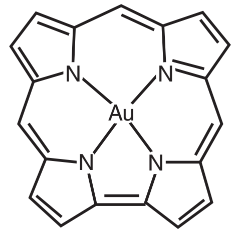


Platinum porphyrin



gold corrole

Cameroonian chemist Kolle E. Thomas, a colleague of the authors, shows a flask of brilliant peach-red *gold corrole*, which phosphoresces in the near-infrared. In the presence of light and molecular oxygen (O_2), excited gold corrole molecules kick the oxygen molecules to a highly reactive excited state that will react with almost all organic matter. Gold corroles (like platinum porphyrins, which have similar properties) thus may emerge as tools for a light-mediated cancer treatment called *photodynamic therapy*.

tion for snatching electrons from other molecules and thereby regaining their preferred lower-valent states with an intact 6s lone pair. Higher-valent Tl, Pb, and Bi compounds thus serve as valuable oxidizing agents in organic chemistry. Perhaps the most common such compound in everyday life is lead dioxide, which is used in the cathode of your car battery and is essential for getting your car started. Without relativity, your car battery would not be able to deliver sufficient voltage, and you would have to use a hand crank to start your car.

Without relativity, your car battery would not be able to deliver sufficient voltage, and you would have to use a hand crank to start your car.

We might expect even more dramatic relativistic effects in the seventh period. In flerovium, the element below lead, not only is the 7s orbital inaccessible to bonding, but also a large spin–orbit splitting of the 7p levels makes the $7p_{1/2}$ orbital unable to participate in chemical bonds. As only the 7s and $7p_{1/2}$ orbitals are occupied, it is possible that flerovium may act as a pseudo-noble gas. Experiments suggest that flerovium is more volatile than expected for a metal. Whether it is best described as a metal or a noble gas remains currently unresolved, partly because so few atoms of flerovium have ever been synthesized.

Indeed, the inert pair effect is not the only relativistic effect that should become much more dramatic in the seventh period. For example, the elements below gold and mercury, roentgenium and copernicium, should have very highly oxidized states. Gold already has a maximum valence of 5, as in the compound Au_2F_{10}, thanks to its scalar relativistic effects. But the even stronger relativistic effects on roentgenium should allow it to manifest a heptavalent state, in RgF_7. Likewise, although mercury normally exhibits a maximum valence of 2, its heavier sibling copernicium has been predicted to exhibit valence states of 4 or even 6, in such molecules as CnF_4 and CnF_6. All of this fascinating superheavy chemistry remains to be confirmed.

Light Where None Is Expected

One of the most widely seen effects of relativity in chemistry shows up as light in the dark. When a molecule is brought into an excited electronic state, for instance by an electric discharge as in neon signs or by the irradiation of light, it will rearrange and eventually emit the excess energy as radiation, often as visible light. This process is referred to as *fluorescence* and happens so fast that to the naked eye it appears instantaneous. However, some compounds glow in the dark with no apparent source of energy to excite the molecules. We see examples of this process everywhere, from safety signs to glow-in-the-dark stickers. Compounds with long radiation times are said to be *phosphorescent*—and the origin of their behavior can be traced to relativity (*see figure on page 165*).

In classical, nonrelativistic theory, there is no way for light to change the overall spin state of a molecule. However, spin–orbit coupling provides a backdoor mechanism, as a result of spin no longer being a pure quantum number. Consider a molecule in its ground state, in which all the electrons are paired and distributed across the lowest-energy orbitals. Using light, we may excite one of the electrons into a higher-energy orbital. Still, for each electron that is spin-up, there is an electron that is spin-down. Spin–orbit coupling, however, may open up a pathway that exchanges spin for orbital angular momentum. This effect will create a new state in which the two unpaired electrons are in different orbitals, but with *parallel spin*. When spin–orbit coupling is weak, this arrangement typically traps the molecule in the excited state for a relatively long time, as long as a few seconds, before it radiates energy (that is, phosphoresces) and decays to the ground state.

In the second half of the 20th century, the American chemist (and gay rights pioneer) Martin Gouterman developed an intriguing approach to phosphorescent materials. He took a class of ring-shaped molecules called

porphyrins, which are known to be a natural part of the hemoglobin found in our blood (*see "Porphyrins: One Ring in the Colors of Life," May–June 2011*). Gouterman inserted a platinum atom at the center of the ring, the spot occupied by an iron atom in hemoglobin. The resulting platinum porphyrins were found to exhibit long-lived phosphorescent states (with two parallel spins). Besides phosphorescence, the excited platinum porphyrin molecules could transfer their excess energy to molecular oxygen, whose forms the basis of a light-mediated approach to cancer treatment called *photodynamic therapy*. Many porphyrins and corroles tend to localize in cancer cells. When a tumor is exposed to light of an appropriate frequency, the gold corrole that has localized in it will generate singlet oxygen, ultimately killing the cancer cells. Although we have only demonstrated the concept in vitro (on cancer cells in a test tube), it is gratifying to think that thanks to relativity, gold and rhenium corroles may one day save lives.

Auroras involve spin–orbit coupling-mediated light emission from small atoms and molecules that are abundant in the upper atmosphere.

lowest-energy form (the one that we breathe) also has two unpaired electrons with parallel spins but for reasons other than relativity. In so doing, the platinum porphyrins returned to their ground states, while kicking the oxygen molecules to an excited state with paired electrons, called singlet oxygen. Molecular oxygen thus kills or "quenches" the phosphorescence of platinum porphyrins and similar light-emitting molecules. In the 1990s, Gouterman brilliantly exploited this property to devise platinum porphyrin–based pressure-sensitive paints that can detect the partial pressure of oxygen on airplane wings, a technology that is widely used today in the aviation world.

Other researchers have used phosphorescence quenching of platinum porphyrins to map oxygen concentration in tumors, a critical aspect of tumor biology that can be exploited for cancer treatment. In our laboratory, we are using another class of ring-shaped molecules called *corroles* to go a step further (*see figure on page 166*). Thanks to spin–orbit coupling, gold and rhenium corroles also exhibit long-lived excited states with two unpaired electrons, which can transfer their excess energy to generate singlet oxygen. It is a molecule that reacts voraciously with any and all organic matter, including cells and tissues—a property that

Relativistic effects are no longer mere curiosities or anomalies in chemistry. Scalar relativistic effects permeate the chemistry of the heavier elements. They explain many of the chemical differences between elements in the fifth and sixth rows, and should be a major determinant of the properties of superheavy elements, whose practical significance is still unclear. Spin–orbit coupling, another consequence of special relativity, underlies the phenomenon of phosphorescence, and offers major untapped potential for medical imaging and therapy.

Relativity also makes the world more beautiful. For much of the year, working as we do at the world's northernmost university, we get an almost nightly reminder of the effects of relativity in the form of the aurora borealis, or northern lights. Auroras involve spin–orbit coupling-mediated light emission from small atoms and molecules such as O, O_2, and N_2, which are abundant in the upper atmosphere. Although we understand in some detail the physics and chemistry involved, they never fail to fill us with a sense of mystery and wonder.

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The Math of Beach Pebble Formation

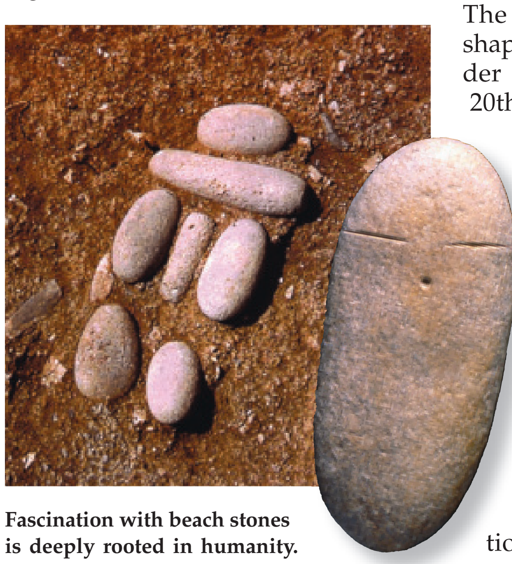
Modeling how abrasion shapes objects has challenged scientists for centuries, from Aristotle to planetary geologists studying Mars.

Theodore P. Hill and Kent E. Morrison

More than 2,300 years ago, Aristotle pondered the shapes of beach stones and proposed that the abrasion of a pebble is more rapid at locations farther from its center, because those regions can receive greater abrasive impulses. He concluded that beach stones evolve toward spheres. But the pebbles used in designs from Stone Age ceremonies (*see images to the right*) to modern art are not spherical at all. Rather, they have the familiar oval shape of the stones shown in the image on page 170 of a beach on Banks Peninsula in New Zealand.

In 1877, geologist W. T. Black presented a paper with his analysis of the oval pebble shapes he had observed at Dunbar, a coastal town in Scotland, providing what is almost certainly the first attempt at numerical classification of pebble shape dimensions (*see the illustrations at the top of page 171*). Black did not mention Aristotle's previous work, and his observations contradict the ancient philosopher's conclusion that beach stones evolve toward spherical shapes. He reported that "the pebbles seem as if their rounded ovoid shape were due to like actions as produce the ovoid shape of a cake of soap after much use, viz. a sliding motion in the palm of the hand, and with an occasional rolling of the mass round." Following his report, other geologists recorded similar observations of the oval shapes of beach pebbles, but apparently no experimental work was performed.

Careful experimentation and modeling would be needed to settle the contradictions between Aristotle's theory about spherical pebbles and Black's observations of ovoid ones. The math behind this abrasion process is quite complicated. Progress was slowly made on this niche topic through the 20th century and into the 21st, but mathematicians and physicists are still working out the details today.



Courtesy of J. Perrot; © The Israel Museum, Jerusalem

Fascination with beach stones is deeply rooted in humanity. In Stone Age societies, they were used in ceremonial art. For example, the image above shows a human figure made of pebbles from an Early Natufian gravesite near Eynan, north of the Sea of Galilee, circa 12,000 BCE. The inset on the right shows a Neolithic pebble figurine dated to 8000 BCE.

Lord Rayleigh's Experiments

The first laboratory studies of the shapes of beach stones evolving under frictional abrasion began in the 20th century with the experimental and theoretical work of Robert Strutt, the fourth Lord Rayleigh (son and biographer of the third Lord Rayleigh, who was awarded a 1904 Nobel prize for his discovery of argon). Lord Rayleigh entered the University of Cambridge in mathematics in 1894 but switched to natural science, where his scientific curiosity led him to ask questions about the ultimate shapes of pebbles.

To try to answer these questions, Rayleigh performed laboratory experiments abrading pieces of chalk. He found that his experimental apparatus could reproduce flattened oval disks very similar to those he found on beaches (*see the figure on the bottom of page 171*). Although both the 19th-century geologists and Rayleigh apparently studied the shapes of only homogeneous stones, the characteristic ovals they reported have also been observed in nonhomogeneous beach stones, such as those shown in the figure at the top of page 172.

Up to this point, no formal mathematical work on the shapes of stones

QUICK TAKE

Aristotle proposed 2,300 years ago that the abrasion of a pebble on a beach tends to result in spheres. But in reality, beach stones are generally ovoid.

Aristotle assumed that pebbles are abraded uniformly in all directions. But not all points on the surface of a stone are equally likely to be in contact with the beach.

Implications of understanding this abrasive process range from coastal zone management under changing climate conditions to insights about the geology of Mars.

Panther Media GmbH/Alamy Stock Photo

A cairn made from stones found on a beach in Cape Agulhas, South Africa, offers various examples of the classic ovoid shapes that can be found on coasts around the world. Mathematicians have only recently been able to explain why beach stones tend toward ovals, not spheres.

evolving under frictional abrasion had been done. More than a quarter century after Rayleigh's experiments were published in 1942, William Firey, an American mathematician at Oregon State University who specialized in the geometry of convex bodies (objects without dents or holes), made the first mathematical breakthrough on shapes evolving by abrasion. Using the intuitive idea that sharp points erode more rapidly than flat regions, he summarized his idea in a simple and elegant form. In describing these results, the *rate of ablation at x* means the inward rate of frictional abrasion of the stone perpendicular to its surface when it is in contact with the beach at point x on its surface. With this terminology, Firey's model for the evolving shape of a stone undergoing abrasion on a beach is the *curvature-only model*, which states that the rate of ablation at x is proportional to the curvature of the stone at x.

Translating this principle into formal mathematics as a deterministic partial differential equation, Firey was able to prove that under this curvature-only model, all convex stones become spherical in the limit. The figure on the bottom of page 172 illustrates a computational solution to this model in the two-dimensional setting with three different starting shapes. Over the next few decades, other theoretical mathematicians, including Ben Andrews at the Australian National University, extended Firey's results with models where they could prove convergence to spherical shapes.

But a critical assumption dating back to Aristotle's model, and still present in Firey's and subsequent models, is that the pebbles undergo *isotropic* frictional abrasion, meaning the pebbles are abraded uniformly from all directions.

Courtesy of A. Berger

Stones with flattened oval shapes accumulate with the tides on a beach on Banks Peninsula in New Zealand. Aristotle thought that beach stones must evolve toward spheres, but examples around the world contradict his theory.

All points on the surface of the pebble are assumed equally likely to be in contact with the abrasive plane of the beach. Equivalently, the contact time with the beach on the surface of the pebble is assumed to be the same in all directions. One example of isotropic frictional abrasion is a pebble in a standard rock tumbler, in which all shapes converge toward spheres. Observations in nature, however, suggest that the shapes of beach pebbles are almost never spherical.

One example of isotropic frictional abrasion is a pebble in a standard rock tumbler, in which all shapes converge toward spheres.

Why No Round Pebbles?

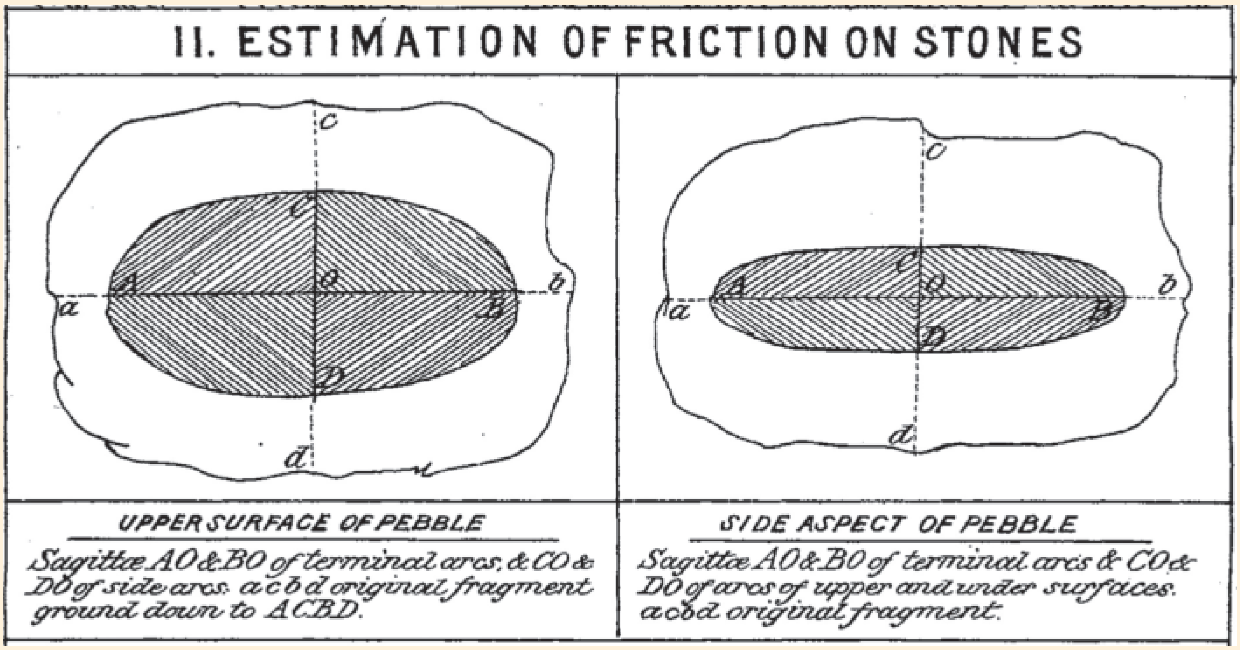
In isotropic models such as those of Aristotle, Firey, and Andrews, a spherical shape is in *stable (attracting) equilibrium*, and any shape close to a sphere will become more spherical. But even early researchers reported that beach pebbles never actually approached the spherical, and Rayleigh specifically observed "a tendency to change away from a sphere," meaning that spherical pebbles are in *unstable (repelling) equilibrium*. Clearly, a spherical pebble is equally likely to be abraded in every direction, so initially it is in equilibrium. Once some abrasion on a beach has occurred, however, it moves away from a spherical shape, not back toward it. To see intuitively how this instability could happen under frictional abrasion alone, consider the thought experiment of the abrasion of a sphere shown at the top of page 173.

Instead, real beach pebbles and artificial pebbles from laboratory experiments typically have the oval shapes seen in Black's and Rayleigh's observations, and the question of what these oval shapes are and what natural physical processes might lead to them motivated us to investigate this question.

The Missing Randomness Factor

Given our interest in probability, we noticed that an essential component in this intuitive argument is that not all points on the surface of a stone are equally likely to be in contact with the beach—that is, the abrasion process is necessarily *nonisotropic*. Assuming that the energy required for the frictional abrasion of a beach stone is provided solely by the energy of unpredictable incoming waves, the point of contact of the stone with the beach is a time-varying random variable.

If the inward ablation of a stone at a given point on its surface is an infinitesimal distance d every time that point hits the abrasive surface (the beach), then in n hits at that point, the resulting inward abrasion will be nd, the product of the inward rate and the number of

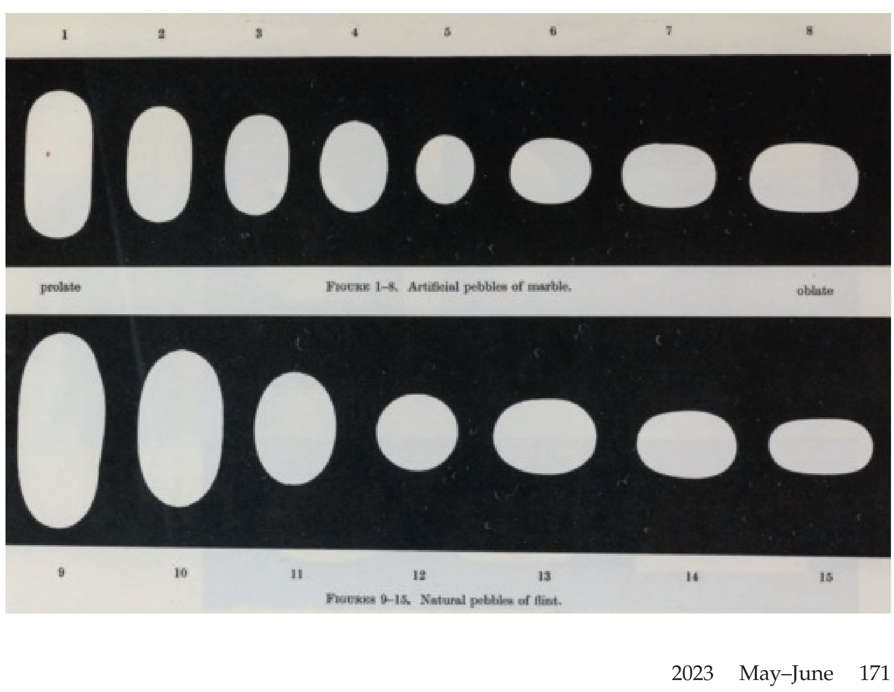


Sketches by geologist W. T. Black from his 1877 paper on his observations of stones on the beaches of Dunbar, Scotland, illustrate their typical dimensions from the top (*left*) and side (*right*). He observed that "the ovoid shape seems to be taken by all sorts of stones, from the soft sandstone to the hard quartzite, and may therefore be independent of mineral composition, or relative hardness of stone."

times it is abraded at that point. Still assuming that abrasion is proportional to curvature, this simple product principle led us to propose the following model: The rate of ablation at x is proportional to the curvature at x multiplied by the expected contact time at x.

How can the random contact time be modeled? In a pebble undergoing frictional abrasion on a beach, both the shape of the pebble and the dynamics of the waves play crucial roles in the contact times at various points on the surface of the stone. If the waves are consistently very small, pebbles will tend to rest in one stable position, and the low energy of the waves will cause the pebbles to grind down to a flat face on that side, much like a standard stone grinder called a *flat lap polisher* is designed to do. The relative time that other points on the surface of the pebble will come into contact with the abrasive beach plane is very small. At the other extreme, if the random waves are regularly very large, then it is likely that all

Robert Strutt (*left*), the fourth Lord Rayleigh and son of the Nobelist who discovered argon, conducted the first laboratory studies of beach stone formation in the early 20th century. The figure on the right shows artificial pebbles of marble (*top row*) that were abraded in his laboratory, and natural pebbles of flint (*bottom row*) that he collected on a beach.



Courtesy of the Royal Society (3).

Courtesy of E. Rogers

Three isolated beach stones collected by the first author illustrate the apparent prevailing oval shapes of beach stones, even when the stones are not homogeneous. The stones on the left and at center are from Montaña de Oro State Park in California and have holes that were made by boring clams. The coral stone on the right is from a beach cave in Negril, Jamaica. These stones all fall within a length of 10 to 12 centimeters.

exposed surface points of the pebble will come into contact with the beach about equally often, meaning the pebble will be undergoing nearly isotropic abrasion as seen in a rock tumbler and will become more spherical.

To see how the shape of a pebble plays a role in how often different points on its surface are in contact with the beach, note that to lift the pebble in the figure on the bottom of page 173 to abrasion position *c* requires more energy than to lift it to position *b*, and *b* requires more energy than *a*.

Analogously, to see how wave dynamics affect contact time, the solid curve in the figure at the top of page 174 depicts a typical contact time distribution for the hypothetical pebble on the left under moderate random wave action, and the dotted line represents the classical isotropic framework where all points on the surface of the pebble are equally likely to be in contact with the beach, as might occur in a rock tumbler or beach with consistently huge waves.

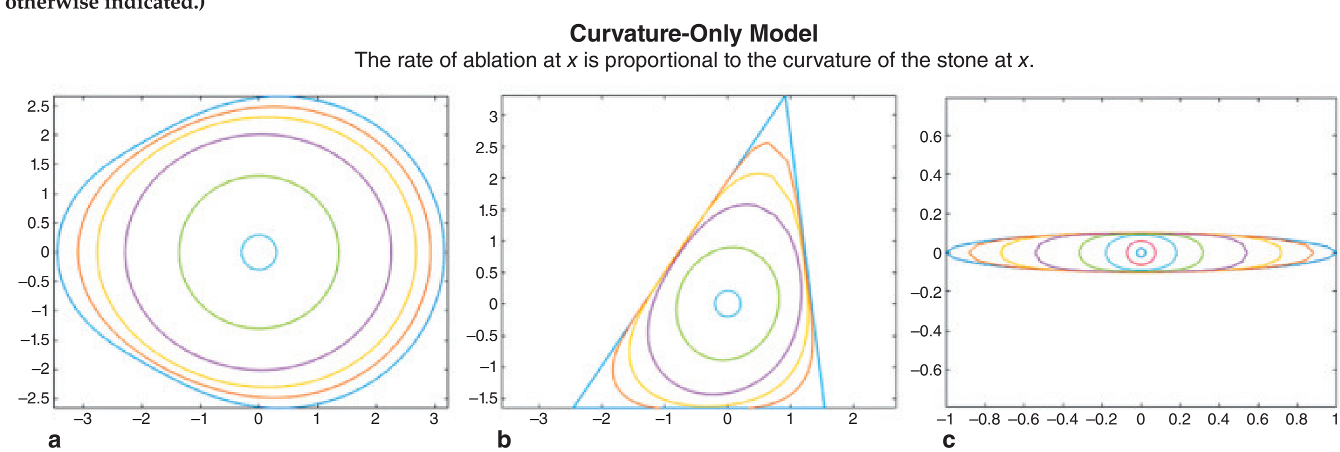
How Oval Shapes Arise

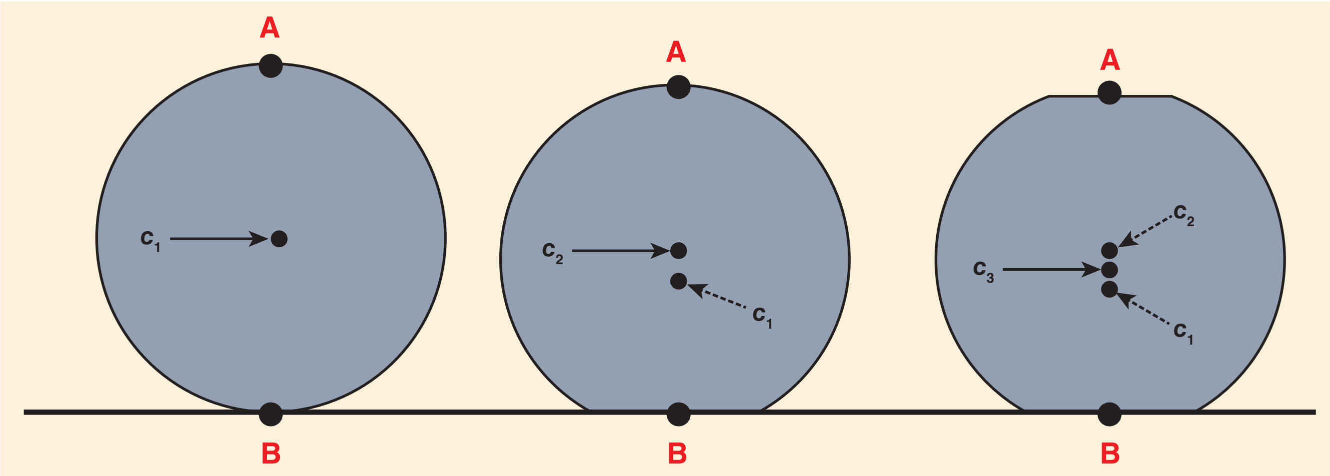
In modeling a complicated physical process, such as the frictional abrasion of pebbles on a beach, there is typically a trade-off between precision and simplicity. For example, the abrasion of beach pebbles also depends on small aerodynamic and hydrodynamic forces, the relative hardness of the stone and sand particles, and even the tiny variability in gravitational forces. As noted by Fields medalist Timothy Gowers of Cambridge, "When choosing a model, one priority is to make its behavior correspond closely to the actual, observed behavior of the world. However, other factors, such as simplicity and mathematical elegance, can often be more important."

Consider a single, fist-sized, nonspherical, homogeneous stone that is eroding by friction as it is rolled about by ocean waves on a flat, sandy beach. Assume that when a wave comes in, it rolls or lifts the stone to the point of contact with the beach such that the potential energy of the stone in that position is proportional to the wave crest height—larger waves will lift the stone's center of mass higher.

Our objective was to discover a model that was simple and physically intuitive, even though it might not be solvable by today's mathematics.

In William Firey's 1974 model, all shapes—including elongated ones—evolve toward spheres. The images below show computer-generated deterministic-continuous solutions to the model, starting with three different initial convex shapes. (Figures are courtesy of the authors, unless otherwise indicated.)





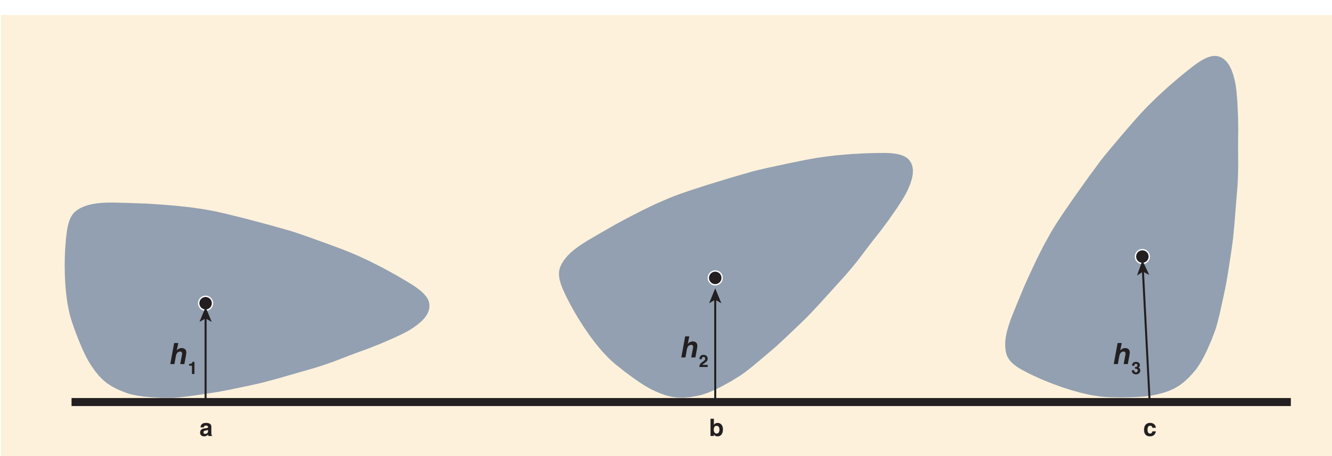
As one side of a spherical stone (*left*) is ablated, that position then becomes a stable equilibrium, as does point A diametrically opposite, and the abrasion process then becomes nonisotropic (*center*). Hence, the most likely directions for the stone to be ablated next are in directions A and B (*right*). The centers of gravity of the stones from left to right are at c_1, c_2, and c_3, respectively.

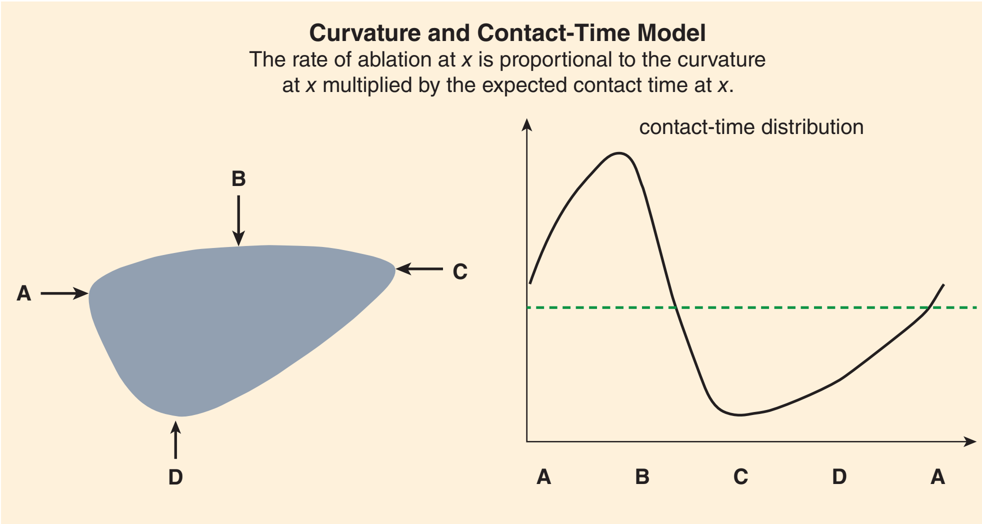
Note that if the expected number of waves needed for the stone to come into contact with the beach at point x_1 on the surface of the stone is twice the expected number of waves needed until point x_2 comes into contact, then over time, point x_1 will be in contact with the beach half as often as point x_2. That is, the likelihood of the stone being in contact with the beach at a given point on the surface of the stone is proportional to the reciprocal of the expected waiting time to hit that point.

Real ocean waves are not exactly periodic or predictable like a sine or cosine wave is. Both the times between successive crests and the heights of those crests are random variables. How often do waves of various crest heights occur? A standard assumption in oceanography is that successive random wave crests follow a classical power law called the *Pareto distribution*. Pareto random variables are characterized by the fact that in an independent sequence of such variables, the expected time until a value h (such as wave height) is reached is proportional to a fixed power p of h. For example, if $p = 3$, then the expected number of waves needed to reach a crest with a height of at least 2 meters is $2^p = 2^3 = 8$ times the number of waves expected to reach a crest height of at least 1 meter. Thus, the average contact times of various points on the surface of the stone with the beach depend critically on the power factor p of the underlying Pareto-distributed random wave energy.

Assuming that the random wave crest heights follow a Pareto distribution with power parameter p, the expected number of waves until a crest of at least height h occurs is proportional to h^p, so the expected contact time is proportional to its reciprocal. That is, in this case the contact-time factor in the *curvature and contact-time model* is simply $^1/h^p$. Because the instantaneous rate of ablation at a point of contact is assumed to be proportional to the curvature at that point (again, sharper points erode faster), this equation yields the prototypical special case of the curvature and contact-time model, which states: The rate of ablation at x is proportional to the curvature at x divided by the pth power of the vertical distance $h(x)$ from x to the center of mass of the stone.

The potential energy of a stone in a given position is proportional to the vertical distance h from its center of gravity to the beach, so to raise a stone from position a to position c requires more energy—a larger wave—than is required to raise it to position b, because h_3 is greater than h_2. Thus, the abrasive contact time in position b is greater than that in position c, simply because waves large enough to raise it to position c are less common than those large enough for the other positions.





The solid curve in the graph on the right depicts a typical contact-time distribution for the hypothetical stone on the left under moderate random wave action. Note that the point B is more likely than the other three points to be in contact with the beach, and hence the time spent abrading at that point is greater than the time spent at the other points. Similarly, the contact time at point C is less than that at the other points. The dotted line represents the classical isotropic framework, in which all points on the surface of the stone are equally likely to be in contact with the beach, as in a rock tumbler or on a beach with consistently high waves.

In this model, the different roles of the three essential rate-of-abrasion factors are readily distinguishable: (1) the curvature of the stone at the point of contact x; (2) the global shape of the stone via the contact point's vertical distance $h(x)$ from the stone's evolving center of mass; and (3) the power p of the Pareto wave process, which reflects the intensity of the waves. Note that these three factors are independent. Because any reasonable model of the evolving shapes of beach stones should include all three factors, this curvature and contact-time formulation may satisfy Gowers's criteria of simplicity and elegance in selecting a model.

Computer Experiments of Abrasion

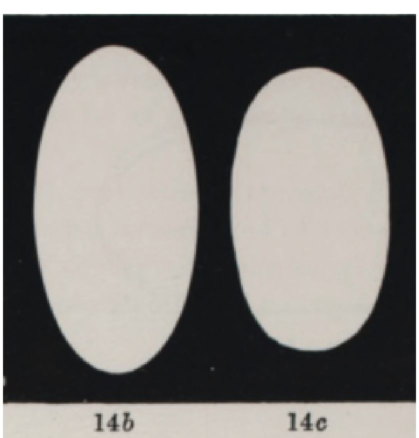
Like Firey's and Andrews's partial differential equations describing the curvature-only model, our Pareto model is an equation that is simple to state. But unlike theirs, ours is a complex "nonlinear partial integro-differential equation" that the current state of mathematics is unable to solve. In particular, the equations for the limiting oval shapes are not known. But our objective was not to formally prove convergence to these mysterious ovals, but to discover a model that was simple and physically intuitive, even though it might not be solvable by today's mathematics. That is, there might not be a known limiting equation or a mathematical proof of the shape's evolution.

Using modern algorithms for approximating the solution of differential equations, however, the evolving shapes may be computed numerically. An example of this method to approximate the evolution of shapes under the Pareto-wave and curvature model is shown on the facing page. Rayleigh specifically noted that these limiting shapes are not ellipses, and he demonstrated this experimentally by starting with a stone with an elliptical shape, which after ablation assumed a nonelliptical shape (*see the figure below*). As of today, it is known that these limiting oval shapes are not ellipses, but the equation for them has not yet been discovered.

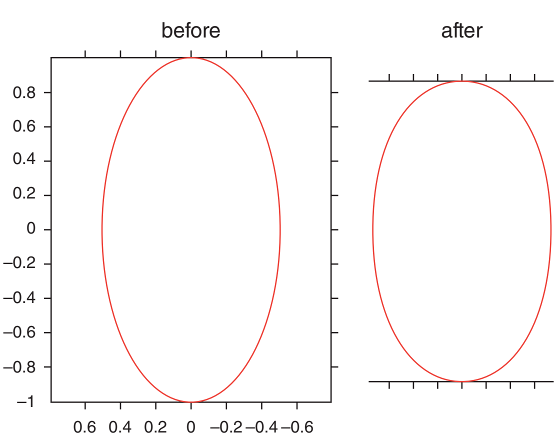
Practical Applications

The evolving shapes of objects undergoing various forms of abrasion has become an important area of research, both theoretical and experimental. For instance, a key to effective coastal zone management is improved understanding of the abrasion process on shorelines due to the rise in relative sea level, along with the socioeconomic changes at the coast that are predicted to take place in the 21st century. And in another example, the strength of concrete-like composites that include pebbles is directly related to their shapes, and numerical modeling indicates that the least breakage load corresponds with the narrowest diameter of oval pebbles.

The shapes of worn stones often yield important clues to the geological and environmental history of the strata where they are found. Also, abrasion and fragmentation phenomena play a key role in space exploration, because of the ac-



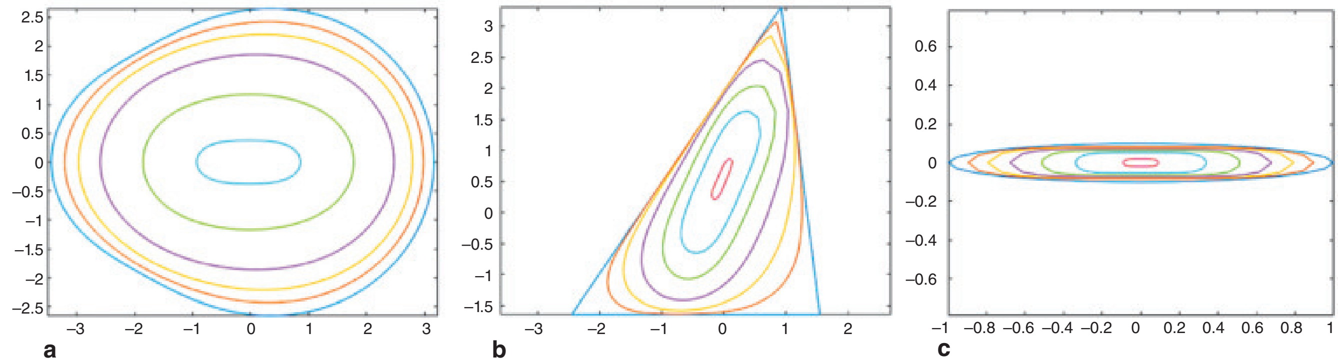
Courtesy of the Royal Society



Lord Rayleigh observed, both experimentally and in fieldwork, that the limiting oval shapes of beach stones are not elliptical. To verify this observation, he abraded an initially elliptical stone (*14b, far left*), resulting in the nonelliptical oval (*14c, middle left*). To see how closely the new Pareto-wave and curvature model approximates his laboratory results, a computer simulation (*right*) shows the abrasion of an exact ellipse when the Pareto power is $p = 2.2$.

Pareto-Wave and Curvature Model

The rate of ablation at x is proportional to the curvature at x divided by the pth power of the vertical distance $h(x)$ to the center of mass of the stone.



In the Pareto-wave model, which assumes that wave crests follow a Pareto distribution, all shapes tend toward ovals rather than spheres. These three images show computer-generated solutions to the Pareto-wave and curvature model, with the power of the Pareto wave process at $p = 3$, starting with the same three initial shapes as in Firey's model shown at the bottom of page 172.

cumulation of space debris over recent decades. Knowledge of the evolving shapes of this debris as it undergoes collision and abrasion with other particles is essential to estimating the life span of the debris and to assessing the risk it presents for satellites and manned space missions. (*See "The Dilemma of Space Debris," January–February 2014.*)

Recognizing the importance of better understanding the natural evolution of shapes in many contexts, the Hungarian Academy of Sciences established a Morphodynamics Research Group in 2017 at the Budapest University of Technology and Economics. The group's focus is "mathematical and physical models of shape evolution with emphasis on geophysical and planetological applications, such as sand grains, pebbles, ventifacts, rock profiles, [and] asteroids." This multidisciplinary research group has made significant progress on the evolution of shapes of objects such as beach stones and river rocks that decrease in size because of abrasion (both frictional and collisional) or chipping. They have also advanced research on the formation of objects such as sedimentary grains called *ooids*, which increase in size through crystal growth or the accumulation of deposits.

A recently developed method to quantitatively estimate transport distance of river pebbles on Earth from their shapes alone was used to draw conclusions about the ancient history of rivers on Mars.

Two members of that research group, geophysicist Douglas Jerolmack at the University of Pennsylvania and mathematician Gábor Domokos at Budapest University, reviewed rocks analyzed by the Mars rover Curiosity. They wanted to know whether shape alone could be used to interpret the transport history of river pebbles. Their team produced the first-ever method to quantitatively estimate the transport distance of river pebbles on Earth from their shapes alone, and used it to draw conclusions about the ancient history of rivers on Mars. Planetary scientists have fiercely debated how much water was on Mars and how it moved, issues that could indicate whether the planet once could have supported life. Jerolmack and Domokos have concluded that the rivers on ancient Mars were mighty enough to have rolled these pebbles tens of kilometers! From earthly beaches to outer space, we are still building on Aristotle's legacy of scientific curiosity.

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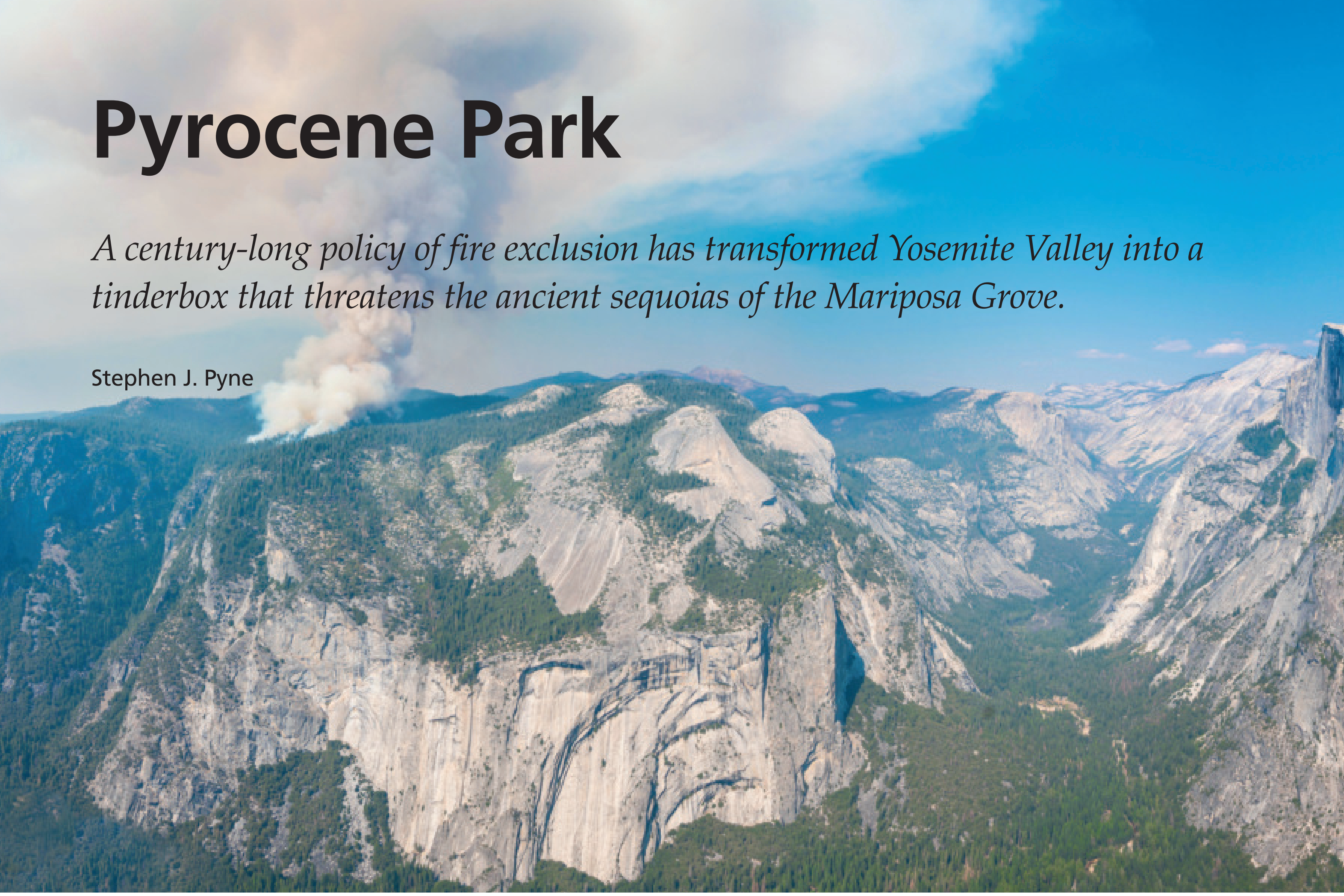
Pyrocene Park

A century-long policy of fire exclusion has transformed Yosemite Valley into a tinderbox that threatens the ancient sequoias of the Mariposa Grove.

Stephen J. Pyne



A smoke plume from the Tenaya Fire in September 2015 punctuates the spectacular vista of Yosemite National Park, as seen from Glacier Point. The long-standing practice of quickly suppressing all fires led to the growth of dense vegetation and the deterioration of ecological integrity. With climate change as a performance enhancer, high-severity fires are now threatening even mature sequoias.

Stand at Glacier Point and you'll instantly understand why it is one of North America's iconic overlooks. The great trough of Yosemite Valley in California fills the foreground below and, with almost gravitational pull, carries the eye eastward to the crest line of the Sierra Nevada mountains. With its sheer granite walls, waterfalls that plunge hundreds of meters, and uniquely sculpted stone monoliths (such as El Capitan and Half Dome), words such as *monumental* hardly do justice to the scene. It's a landscape shaped by Pleistocene ice that widened and deepened valleys, rounded exposed granite, cached boulders and soils, and scoured routes for runoff that eventually became rivers and waterfalls. Even today, its groves of sequoia, a charismatic megaflora, inhabit sites where the ice failed to enter.

Pivot south, however, and you'll see a scene as aesthetically bland as Yosemite Valley is gripping. The eye passes over it as fast as a stone skimming across a lake. The Illilouette Creek Basin is broad and rumpled, its granite surface camouflaged by forest, lacking the bold monoliths that make Yosemite Valley instantly recognizable. In the Illilouette, every iconic feature in Yosemite Valley has seemingly been inverted.

Yet a century after Yosemite National Park was first established, the Illilouette became a serious focus for management. The reason? It is a landscape informed by fire as fully as the Yosemite Valley was by ice, and, equally, its rock-exposed perimeter tends to contain fire within it, rendering it a kind of fire island. In 1972, those properties inspired a bold experiment to restore natural fire in the Illilouette. This effort involved ending the suppression of fires kindled by lightning strikes and allowing them to burn freely (under the right conditions). Amid national enthusiasm for all things wild, and in a place chartered to preserve the natural scenery "unimpaired" for future generations, reinstating a natural process seemed an obvious thing to do. At that time, the fire community of fire officers, administrators, and researchers regarded the nation's public lands as headed toward an

QUICK TAKE

Yosemite National Park is still recovering from a century of strict fire prevention policies, which left the valley overgrown and at increased risk for catastrophic wildfires.

The antifire policies arose from good intentions, poor understanding, and elitist assumptions, including that the Indigenous practice of controlled burns was primitive and harmful.

Prescribed burning returned to Yosemite in the 1970s, but it has proven difficult to undo, both ecologically and institutionally, the legacy of fire exclusion.

imageBROKER/Alamy Stock Photo

impending disaster. Thanks to land use, including the practice of fire exclusion, wildlands were reorganizing in ways that built up combustible vegetation to dangerous levels and allowed ecological dry rot to damage fire-impoverished landscapes. The Illilouette experiment was an attempt to let nature recover, using nature's own means.

Over the next 50 years, the horizon of that project lengthened beyond the granitic rim of the Illilouette. What started as a crisis visible in public wildlands metastasized into a generally acknowledged planetary calamity. The Pleistocene has evolved into a Pyrocene. Everywhere, fire is replacing ice. Uncontrollable wildfires ramble across open lands; untamed fires transform biomes from peat and forest into plantations and pastures; and fires encased by machines bloat the atmosphere with greenhouse gases, acidify the oceans, and enable a global wave of extinction. Even the cars, buses, and asphalt that traditionally defined Yosemite's management obsessions are possible only because of humanity's combustion habits. In the Pyrocene, every defining trait of an ice age has seemingly been inverted into a fiery equivalent.

From the beginning, Yosemite's fires provoked controversy. Authorities denounced fire as a kind of vandalism, an emblem of unenlightened primitivism, and an index of social disorder.

Reforming the Landscape

Yosemite is special. In 1864, amid the bitter Civil War, the U.S. Congress set aside Yosemite Valley and the Mariposa Grove of giant sequoias, ceding management to the state of California. At the time, the Miwok Indigenous people annually burned both the valley and the grove to facilitate access and hunting and to prevent bad fires. Between fires caused by lightning strikes and by travelers burning along trails (to keep paths clear and assist hunting), the backcountry burned as well. Smoke was constant and, according to early observers, scorch marks were visible on nearly every tree.

From the beginning, Yosemite's fires provoked controversy. Authorities denounced fire as environmentally damaging; a kind of vandalism; an emblem of unenlightened primitivism; and messy—an index of social disorder. These were views commonly held by Europe's elites, and accepted as axiomatic by foresters. They applied as much to Europe's traditional fire users (and settler newcomers) as they did to Indigenous peoples in colonies from California to India and Australia. The United States' first professional forester, Bernhard Fernow, dismissed the causes behind the country's simmering landscapes as "bad habits and loose morals." Western Australia's conservator of forests, Stephen Kessell, grumbled that "only a few years ago the general public felt no compunction about setting the wild and untended forest alight whenever opportunity presented itself."

Nearly everywhere that European-inspired modernity went, it found landscapes routinely ablaze, and everywhere authorities made fire's suppression a foundational doctrine of conservation. Yosemite's Board of Commissioners applauded Galen Clark, the first guardian of the Yosemite Grant, for shielding the park from wanton fire. Park commissioner Frederick Law Olmsted, famous for designing Central Park in New York City, denounced "Indians and others" (primarily shepherds) for their promiscuous burning. Even John Muir, the *genius loci* of Yosemite and one of the era's great observers of nature, wrote in 1876 that fire "is the arch destroyer of our forests, and sequoia forests suffer most of all."

Library of Congress

Photographer Carleton E. Watkins captured this image of North Dome around the time of the 1864 Yosemite Grant, which protected the valley and the Mariposa Grove from development. The Miwok Indigenous people had practiced routine burning to ease access and promote hunting and harvesting, but park commissioners instituted a policy of fire exclusion.

But almost immediately, the abolition of fire caused problems. Without routine flushing by flames, young trees filled up both the Yosemite Valley and the Mariposa Grove. Within a handful of years, it became difficult to view the granite walls and towering waterfalls that brought tourists to the valley, while white fir and incense cedar crowded around and obscured the giant sequoias. Worse, combined with windfall, those young woods threatened the giants with wildfire. To those who already distrusted fire, that enhanced threat argued for yet more protection against fire, which set up a cycle of well-intentioned but self-defeating policies. In 1889, wildfire did enter the grove. The failure to halt the flames, combined with other concerns, led Congress to return Yosemite to federal control the next year.

Not all of Yosemite's commissioners had objected to fire. William H. Mills, for example, loudly proclaimed that he had "always respected the ability of the Indians to manage that valley" and that he regarded fire "as a very good method of management." The removal of fire had only catalyzed unwelcome change. Such views were prominent among people who actually lived on the land, as well as several other commissioners and observers. However, the official policy (promulgated by the U.S. Department of the Interior) made fire-starting illegal.

The federal government sent in the U.S. Army to establish firmer control

Courtesy of the Yosemite National Park Archives, Museum and Library

The nine men known as the First Rangers of Yosemite National Park, photographed in 1915, took over from the U.S. Army as guardians of the valley. They maintained the previous policy of preventing and quickly extinguishing all fires, even though the policy remained controversial.

of the forest. Every summer from 1890 to 1914, a cavalry detachment bivouacked outside the Mariposa Grove, and later Yosemite Valley, enforcing rules against trespassing, timber theft, and fires. The army soon appreciated both the extent of burning and its value, and many officers argued for a program of regular burning. Captain G. H. G. Gale noted as "a well-known fact that the Indians burned the forest annually" and then concluded that the "absolute prevention of fires in these mountains will eventually lead to disastrous results."

Nearly everyone in the mountains agreed, except officials. What became known as the "light burning" controversy bubbled up in California during the first two decades of the 20th century. Light burners referred to those who argued that the United States should emulate its Indigenous peoples and routinely burn forests, instead of conforming to European forestry. Foresters saw this movement as a challenge not only to their competence as firefighters but to their credibility and legitimacy as agents of conservation. U.S. Forest Service Chief William Greeley dismissed light burning as, in his words, "Paiute forestry"—referring to the burning practices of Indigenous Paiute peoples. In 1923, a commission convened by California's Board of Forestry ruled against light burning, and the practice became anathema. Fire policy remained unchanged.

Courtesy of U.S. National Park Service

Without wildfires, vegetation grew unchecked in Yosemite Valley, as shown in this 1917 photo of young sugar and yellow pine trees blocking the Yosemite Lumber Company's railroad lines. Notes accompanying the photo state that the trees grew in logged areas, where seeds left on the ground took root because there were no fires to disturb them.

Restoring Fire

The same controversy bubbled up wherever modernity met traditional societies. The same discussion occurred in British India in the 1870s under the rubric of "fire conservancy," with similar splits between those in authority and those charged with executing policy on the ground. Eventually, British foresters had to compromise in practice, though never in principle, and French foresters did the same (by looking the other way). Those in power would never formally acknowledge burning as legitimate land use because it defied the science of the day and bore a stigma of primitivism. Besides, fire was too useful as an emblem of wrecked lands. (It still is: Think of how fire is used today to symbolize the climate crisis.) The public, they argued, would be confused if asked to distinguish between longstanding burning practices and the ruinous burns that feasted on the offal of logging and land-clearing.

Half a century later, Yosemite forester Emil Ernst noted that: "Up until about 1906 this policy of fire suppression was openly and actively condemned by the highest responsible officials who, however, disregarded their own opinions and carried out the fire suppression and fire prevention policies with which they heartily and honestly disagreed." That intellectual dissonance became institutionalized. In reality, the authorities had it backward. The real menace was mindless firefighting, not fire-lighting.

In 1930, the administrators of Yosemite National Park erected a lookout and a guard station, and began keeping formal records of fires. In 1933, the park was granted the money and muscle it needed to enforce the fire exclusion edict with the arrival of the New Deal, emergency conservation programs, and the Civilian Conservation Corps. Bolstered by that same largesse, the Forest Service announced in 1935 a universal mandate to control every fire by 10 a.m. the next morning. As an administrative edict, it was brilliant—unambiguous, quantitative, dramatic. As a guide to ecosystem health and fire protection, it was hopelessly flawed. It was a policy for cities, not the countryside.

Between 1962 and 1978, a reformation in fire thinking overturned previous doctrine. A new generation saw the same evidence differently, and a gestalt-like switch took place in which what earlier generations had seen as a boisterous forest of the future now looked like dysfunctional woods ready to explode in flame. In 1963, a commission chaired by wildlife professor A. Starker Leopold urged the National Park Service to actively manage its natural estate and cited the overgrown dog-hair thickets of the Sierra parks as a poster child for the need to restore fire.

At the same time, research was progressing on the western slopes of the Sierra Nevada at Redwood Mountain, the world's largest sequoia grove. Most of the site lay along the western boundary of Sequoia and Kings Canyon National Parks, but the University of California, Berkeley, held part as an experimental forest, and under the charismatic leadership of fire scientist Harold Biswell conducted research on the dual threats posed by fire exclusion: Thanks to encroaching woods, wildfire could reach into the crowns of even giants, and the absence of surface fire (which could purge competitors) limited sequoia regeneration. The grove needed fire.

Courtesy of U.S. National Park Service

In 1977, firefighters conducted a controlled burn in Yosemite National Park. Experiments in fire restoration demonstrated the benefits of fires for forest health, including both prescribed burning and managing—rather than extinguishing—natural fires.

Research plots were soon matched with demonstration plots for showing how to recover that lost fire. Most of the park fire staff for Sequoia, Kings Canyon, and Yosemite National Parks learned their skills on the slopes of Redwood Mountain and studied under Biswell or his colleague Leopold. In 1968, the National Park Service replaced the 10 a.m. edict with a policy of fire restoration. Ten years later, the U.S. Forest Service followed suit. Deliberate, prescribed burning was one solution; another was to allow natural fire more room to roam. In 1972, Yosemite designated the Illilouette watershed for an experiment in fire restoration. The Illilouette provided proof-of-concept that became particularly important after the 1984 California Wilderness Act put 95 percent of the park into legal wilderness.

A basin emptied of flame began, patch by patch, to fill up with it. Fire returned as lightning strikes set fuels ablaze (any human ignition was suppressed), some burning new places, some reburning previous burn scars as they rejuvenated. Paradoxically, wilderness status complicated the restoration: It was acceptable to put out fires but not to light them, which meant a steady decay in the total area burned. Moreover, as bad fires worsened in California, it could be awkward to justify keeping Yosemite alight with good fires or to demand that its in-house fire crew tend its home fires rather than rally to the megafires that threatened surrounding lands.

The effort to restore fire was a revolution from the top that struggled to express itself on the ground. Policy could pivot quickly; practice could not.

Managing Fire in an Age of Gigafires

In retrospect, Yosemite's experiment in fire restoration occurred at a benign time. When the Starr King Fire burned almost 1,500 hectares in the Illilouette in 1974, it seemed huge; 20 years later, you needed 10,000 hectares to shock; and 40 years later, 100,000. The term *megafire* was coined after the 2002 season; by 2019, *gigafire* had entered the fire community's lexicon. Legacy fuels were mating with the climate crisis and, as more fires threatened communities and saturated California's skies with smoke palls, it became harder to muster both the resources and the will to manage—rather than simply suppress—outbreaks, however much those massive firefighting endeavors failed and added to the problem.

The effort to restore fire was a revolution from the top that struggled to express itself on the ground. Policy could pivot quickly; practice could not. Most parks and national forests did not make the transition. Rather than being two sides of the same fire-management coin, firefighting and fire-lighting often became rivals. At Yosemite, the two groups had separate programs in separate administrative bunkers. Fire suppression had tradition, equipment, crews, and plenty of money. Fire management, which embraced a pluralism of fire practices, had an office in the attic (literally) of the administrative building, few resources, and scant funding. A failure to control a wildfire would prompt more effort to control it. A failure to control a prescribed fire could end a career. However natural its ignition source, however squarely embedded in legal wilderness, liability resides in the person or agency who decides to monitor, loose-herd, or generally manage fire rather than extinguish it immediately.

The checklists of decision points that govern whether to allow a natural fire to proceed swell with each year, with every new social value identified, with every glitch and stumble in fire practice, and with every personnel transfer into and out of Yosemite. Fire management must cope with the Clean Water and Clean Air Acts, with the Endangered Species Act, with the Wild and Scenic Rivers Act, with potentially threatened cultural resources, with visitor safety, with regional fire danger and available resources, with personalities among cooperators, with punishing drought, and on and on. Any fire can be shut down for one of many reasons: Gateway communities and concessioners don't want flame and smoke to discourage tourists or to force the park to close; invasive plants can spread in the burn footprint; callouts under the California master fire plan can divert crews from prescribed fires.

Noah Berger, Associated Press

A firefighter protects a sequoia tree in the Mariposa Grove during the Washburn Fire, which burned for 28 days in July and August 2022 and blackened 1,977 hectares of forest. Fire management teams must balance the benefits of fires to the health of the Yosemite Valley ecosystem with the need to conserve these ancient, endangered trees.

And then there is the threat of wretched air in the nearby San Joaquin Valley and prolonged smoke in Yosemite Valley, uncertain and unequal funding among aspects of an integrated fire management program, and concerns over the Hetch Hetchy Reservoir (which provides municipal water for San Francisco). Any and all of these threats can encourage fire officers to end a fire. The required compromises are endless, and they all point to fire suppression as a default setting. There is no comparable checklist by which to quicken the reintroduction of fire. Even so, over the past half century, enough fire has gotten in to keep the Illilouette from detonating. Monitoring demonstrates conclusively that the basin is far healthier and more resilient than lands outside the park.

In September 2021, the park arranged for its governing cadre, along with three researchers, to trek into the Illilouette for a three-day retrospective on what 50 years of fire management had wrought. Even as the trekkers readied their gear, two fires along Yosemite's Tioga Road continued to be managed, loose-herded into burn footprints from the previous year. To counter their smoke spreading into Yosemite Valley, two fires in the Illilouette had been extinguished earlier in the summer. The trek demonstrated the difficulties of managing fire today: not only in trying to make up losses from the past, but also in preparing for the compounding threats posed by an accelerating fire epoch. The opportunity to converse over policy and protocols while mellowing out over an evening campfire had disappeared when, two weeks earlier, the park was forced to impose fire restrictions, which left the trekkers huddled around an LED-lit lantern instead of real flames. Some of the best fire officers, fire scientists, and wilderness planners in California were unable to light a fire in a backcountry campfire ring around which they could discuss how to restore fire at a landscape scale.

More tellingly, unfolding events showed that managing Yosemite's fires was no longer something that the park could contain within itself. Three days before the trek, a lightning storm kindled three fires in the park, and another three at Sequoia and Kings Canyon parks; Yosemite's were extinguished, but the remaining fires soon merged into what became known as the KNP fire complex, and its smoke filled the southern horizon of the Illilouette, causing park personnel, including its fire management officer, to be dispatched to Sequoia-Kings. The fires had not stopped by the time the trek ended, and the cadre debated what they meant.

Allying with Fire

Over the past 30 years, fires have hammered at Yosemite's border and sometimes poured through. The A-Rock and Steamboat fires in 1990 forced the park to close for the first time in its history. The Rim Fire that started in 2013 burned 104,130 hectares, some 31,000 of which were within the park. The Ferguson Fire of 2018 surged over Yosemite's western boundary. In 2020, the Castle Fire brushed against the park's southern perimeter, and smoke from border burns compelled the park to close twice. Further afield were all

Bill Lea/Dembinsky Photo Associates/Alamy Stock Photo

In September 2018, a month after the containment of the Ferguson Fire, smoke lingered in Yosemite National Park. U.S. Forest Service investigators determined that superheated pieces of a vehicle's catalytic converter came into contact with dry brush and ignited the fire, which burned 39,214 hectares, resulting in the temporary closure of parts of Yosemite National Park, including the Mariposa Grove.

those emissions from all those fires burning fossil fuels that were collectively unhinging the climate and making climate history a subnarrative of fire history.

The park has stumbled, too. In 2009, a prescribed fire in Big Meadow intended to help protect the gateway community of Foresta escaped and blew up into a maelstrom of public and political criticism. Yosemite's entire fire program was already immersed in a major upheaval in personnel that grumblers likened to a purge. By the time the fire organization regrouped, California was suffering a historic drought that, along with insect outbreaks and fires, would kill an estimated 150 million trees in the Sierra Nevada. Funds in fire budgets not directly related to community protection were stripped away. Fire staff positions went unfilled. Most of the park's needed burns came from wild, rather than managed, fires.

At all levels of Yosemite's administration, fire is now regarded as a critical issue, if not yet an existential one. A new round of reforms and restarts is underway. The park considers its fire program a "beacon" to others, and the park's chief of staff believes the park is now headed into "a golden age of fire management." The fire program has a full roster, and prescribed burns are lighting up Yosemite Valley, while thinning and burning projects are underway at the Merced and Tuolumne groves.

Throughout the 50-year reformation in fire management, Sequoia, Kings Canyon, and Yosemite National Parks had shared knowledge, personnel, and an origin story birthed at Redwood Mountain Grove. What happened to one was an omen for the others. In September 2021, the KNP fire complex worsened, and crews hurriedly cleared around developed areas, draped aluminum foil around the trunks of giant sequoias, and burned out along the Generals Highway that connected the parks' various groves, hoping to back the fire down Redwood Mountain itself.

On October 4, those fires blew up. A *pyrocumulus plume* (a dense cloud of smoke and ash) towered over the largest concentration of sequoias in the world, and an unknown number of mature redwoods were incinerated. Combined with the 2020 season, an estimated 15 to 20 percent of Earth's mature sequoias died. The big trees were famously adapted to fire, but not to the savagery of such burns, or likely to the severity of the maturing fire age. Hopeful observers noted that the KNP fire complex could have been worse, and that the park now had a 35,737-hectare burn scar by which to anchor future treatments such as thinning woods, setting prescribed burns, and managing wildfires.

Nature demands a fire tithe, and Yosemite had managed to pay only part of it through fire restoration—enough to keep going, not enough to pay down the principle. To some observers, the debt was growing faster than it was being paid down. Neighboring Sequoia and Kings Canyon parks had 4,450 hectares of sequoias and, over the 50 years since fire restoration had become policy, it needed to treat only 89 hectares a year, but had failed. Yosemite had secured the Mariposa Grove, its biotic Parthenon, though not the grove's periphery, and had left mostly untreated the overgrown Tuolumne and Merced groves. Even the Illilouette—a showcase project in a showcase park—has never made up its fire deficit. Other, more immediate crises, commitments, and exercises in risk aversion had resulted in half steps, distractions, and diversions, each justifiable at the time, but whose cumulative effect weakened the program.

Yosemite shows what it takes to keep fire an ally rather than an enemy—fire is a relationship, not just a tool. Yosemite also demonstrates how hard this task is, and how what seemed bold in the past might appear feeble when measured against contemporary conditions. Yosemite is a flagship national park, is the best-funded unit for fire management in the entire system, and occupies a prominent place in national fire reforms. Yet it survived by being lucky as much as by being good. Many places are neither.

Even astute observers wrestle with the three-body problem presented by natural fire, anthropogenic fire in living landscapes, and the combustion from burning lithic landscapes. They struggle to truly appreciate the extent to which fire is systemic rather than seasonal, a planetary feature not a biotic bug, a phenomenon whose plumes span from the geologic past into the geologic future. We don't yet fully apprehend the pervasiveness of the fire age that is reforging Earth.

Stephen J. Pyne is a writer, an urban farmer, and an emeritus professor at Arizona State University. His latest book is Pyrocene Park: A Journey into the Fire History of Yosemite National Park *(University of Arizona Press, 2023). This article is adapted from an essay originally published in Aeon (aeon.co). Email: stephen.pyne@asu.edu*

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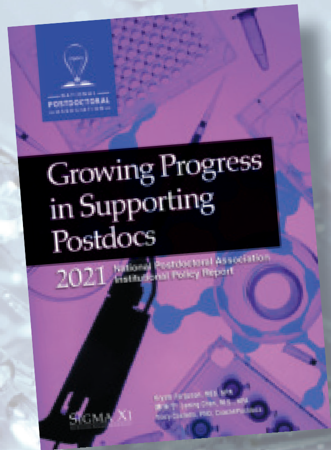

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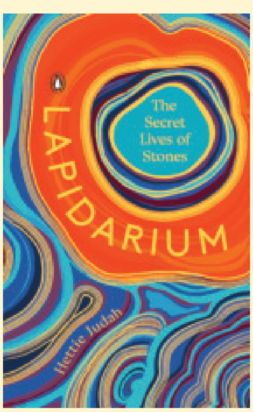
More Than Building Blocks
Hettie Judah explores the history, science, and cultural significance of a variety of stones, bringing them to life through stories and research in her new book, *Lapidarium: The Secret Lives of Stones*.



The Dark Side of Light

Jenny Ouyang

THE DARKNESS MANIFESTO: On Light Pollution, Night Ecology, and the Ancient Rhythms That Sustain Life. Johan Eklöf, translated by Elizabeth DeNoma. 272 pp. Scribner, 2023. $26.00.

I was a graduate student when I first saw the Milky Way. I, along with my future husband and two friends, stared into the immensity of sparkling specks swimming in a ribbon of silk, while lying on haystacks on Favignana, an island off Sicily. My husband and his brother are from Venice, Italy, and my friend and I are from China; all of us grew up in cities on the Bortle scale greater than 7, which means we had never seen a dark sky without the glow of city lights. We remained silent for hours as we stared at the Milky Way. I blinked back tears as I looked into the stars, feeling my own insignificance, surrounded by the vastness of our universe. As urbanization continues to increase, there are more and more of us who will never see the Milky Way, who will never look to the stars to ponder our place amongst the galaxies.

Light pollution is the excessive or poor use of artificial outdoor light at night, which disrupts natural patterns of wildlife and human sleep, contributes to the increase of carbon dioxide in the atmosphere, and obscures stars in the night sky. *The Darkness Manifesto* is a well-researched and beautifully written book by Swedish researcher Johan Eklöf that details the effects of light pollution on animals and humans and is, ultimately, a plea for embracing darkness. As sad as the vanishing of darkness is for humans, it is mostly an emotional loss. For many other species, though, the loss is existential. For a book with darkness in the title, it is mainly about light. The pollution of the night robs us of our appreciation for light, erasing the distinctions and making our lives narrower. It is humans who love the light and who have built civilizations that fear the darkness; this trait has ultimately created a blazing planet of light pollution, affecting more than 80 percent of Earth's populated areas.

The book starts with twilight, describing it as a transitional place for humans, who are only visitors to the night. After all, the night belongs to most of the world's species of mammals and insects, which hunt, hide, and mate in darkness. Eklöf describes how the rhythms of these twilight animals are impacted by light pollution, from the natural chemistry of the light-emitting protein luciferin in sea fire urchin, glowworms, and fireflies, to the disrupted star compasses of migrating birds. All animals have evolved under a natural cycle of light and dark, but light pollution obscures or even obliterates that cycle, changing daily rhythmic behaviors. Light is the most important *zeitgeber*, or time-giver, for our body's circadian clock, which measures each day in roughly a 24-hour cycle. In an increasingly illuminated world, the boundaries of night and day are blurred, changing activity patterns. For example, luciferin emits light, but only starting at twilight, and the star compass of birds works only under clear night skies. Because light is such a powerful environmental cue, if it continues to increase, the existence of these animals is threatened due to vanishing transitional twilight. As Eklöf masterfully spins the tale of these animals, we follow their rhythms into twilight, feeling the loss for baby turtles that wander into the city lights as they search for the sea, and for abandoned clownfish eggs that need the dark to hatch. Each story

builds the tale of an ecosystem in flux with darkness as an ecological niche being disrupted by light.

Eklöf then moves his narrative from twilight animals to those that depend on darkness, as well as the many researchers who study light's effect on darkness, using a rich foundation of historical and current scientific sources. Although the reader grasps the urgency of light pollution, the book, especially the section "Night as an Ecological Niche," jumps from one example to the next without much organization. It would have been helpful if the examples moved in a chronological or taxa-based fashion, but we are left with numerous case studies without a summary of conclusive impacts. However, three examples illustrating the breadth of the topics covered are notable.

First, in the 1840s, Robert Hunt, a physicist, chemist, and artist, discovered that plants germinate and flower under different wavelengths of light. This type of research is foundational for all the current work on light spectra and agricultural needs. Second, founded in 1905, the Krefeld Insect Society in Germany, whose members were priests, publishers, and teachers, joined by a love for insects, sounded the alarm of a mass insect die-off. Their carefully curated collection spanning more than 100 years propelled current research on the "insect apocalypse." As insects are attracted to light, many spinning exhaustively until death near lampposts, light pollution is likely one of the many environmental factors causing their decline. (*For more discussion, see "No Simple Answers for Insect Conservation," May–June 2019.*) Third, the elegant experiments performed in the 1950s by Eleanor and Franz Sauer, followed by Stephen Emlen, demonstrated the capacity of birds to navigate by the stars. They showed that baby birds in open cup nests imprint on the stars based on Earth's rotation, and can be disoriented by artificial light during their migratory paths. These animals are all attracted to light in a "vacuum cleaner effect," with light as an attractant sucking them into its lure. These three examples show the breadth of the taxa covered in the book, from plants to invertebrates to vertebrate animals, and they stood out to me because of my previous research on these topics. For an uninitiated reader on the subject of light pollution, however, the diverse effects on so many organisms might be overwhelming. Organization of the section

UPI/Alamy Stock Photo

In the Cagayan Valley in the Northern Philippines, bats soar out of Callao Cave at dusk.

by taxa or using a single species, possibly the bat, as a common thread to link examples would have helped the reader finish the book with overarching conclusions about the effects of light pollution.

Nothing symbolizes darkness better than bats. Eklöf is a bat researcher, and his love for this quintessential creature of the night comes across throughout the book, including examples from mythology, such as Sri Lanka's lore of the owl as the bat's consort, and the Chinese bat symbol of long life and happiness. Bats, experts at hunting nocturnal insects and avoiding predatory birds, use nighttime as a refuge. Using historical research into how bats can navigate without light, Eklöf writes of blindfolding and ear plugging experiments in the 1700s, showing that blindfolded bats were able to capture prey, but ear-plugged bats were not. It was not until the 1900s, with Donald Griffin's groundbreaking work, that these early experiments were confirmed using high-frequency sounds—echolocation. In the case of increasing streetlamps, there are two losers: the moths that are attracted to the glowing lamps, spiraling until they die of exhaustion, and the light-averse bats that are pushed further into peripheral landscapes. Although Eklöf does not give exact numbers of decline, an increasing number of studies show that bat populations are declining in urban centers globally. Recent work shows that sky brightness has doubled in the last decade; if this trend were to continue, we risk the loss of darkness that so many animals depend on, including bats.

Next, the book moves from the natural world of darkness to the ills of an artificially illuminated planet as it affects both wildlife and humans. As light disrupts our internal clocks and hormone rhythms, there is an increased prevalence of stress, depression, and sleep problems. Night-shift workers have increased risk of tumor formation because light suppresses a natural nighttime peak of melatonin, a hormone essential for sleep. Another direct result of the breaking down of melatonin cycles is a lowered level of leptin, a hormone that regulates appetite. One of the many causes of obesity could be linked to dysfunction of leptin and melatonin levels affected by light pollution. In other words, we "light ourselves obese" and we "light ourselves sick."

Light pollution is a pervasive threat to global health, to the creatures that depend on the dark, and to ecosystem services, such as those provided by pollinating insects and bats. Increasing light pollution has caused the decline of creatures that depend on darkness; some of those being essential for ecosystem function. Thousands of workers in Sichuan Province, China, currently hand-pollinate blossoms that were previously insect pollinated. Sichuan is a 9 on the Bortle scale, a region so brightly lit that it does not sleep; light pollution is one of the hypothesized causes of its native bee decline, along with pesticide use. A human worker can pollinate 10 trees per day, but a small bee colony can handle hundreds.

Similarly, a decline in bat populations in certain areas is also apparent. Bat declines because of light pollution have been reported across Southeast Asia. For instance, rice crops are being threatened by insect attacks and diseases, which are typically alleviated by bat colonies.

Despite all the negative impacts Eklöf describes, the book is ultimately optimistic. "Less is more" is a phrase that can be applied to lighting, Eklöf writes. With the invention of LEDs, lighting is more energy efficient and can also be more easily manipulated. LEDs can be directed and constrained, eliminating unwanted light scattering. Using longer wavelengths of LED light can reduce physiological and behavioral costs, eliminating the harmful blueish light that eats away at our health. We can mimic the natural spectrum of light by controlling intensity, retaining the convenience of artificial light while limiting its erasure of darkness. There is a rise in darkness tourism as people begin to seek out the dark, and at the forefront is legislation recently passed in France limiting how much light can be emitted to the atmosphere. Invoking philosophers from Kafka to Rousseau, Eklöf writes of the dark as our friend, of contemplation in silence when we rest our eyes, of something beyond what we can imagine in light.

The book ends with Eklöf's own "darkness manifesto": to be aware of, embrace, and protect the darkness. His list of actionable items can be followed by all: first to become aware of the darkness, then to avoid blue light at night and talk to those around us about the importance of darkness, and finally to influence our own environment by limiting excessive use of night light. The book does an excellent job of evoking empathy for those animals suffering the loss of night, such that by the end, the reader is appreciative of darkness and wants to protect it. By protecting darkness, we protect our own health and the well-being of our ecosystem, which contains so many creatures dependent on the distinction between night and day. Only by following our inner rhythm and letting our eyes adjust to the dark can we truly see the animals that need the dark to survive.

As diurnal animals, we need the darkness to appreciate the light; it is in darkness that conversations lengthen and silence is profound. Eklöf wonders if his children will be able to take their own children to Lake Tolken to experience shooting stars, both to witness the celestial fireworks above, and the darkness around them needed to see it. I hope that my own children will be able to see the Milky Way, to experience that glorious ribbon of light in the darkness.

In an increasingly illuminated world, the boundaries of night and day are blurred, changing activity patterns.

Jenny Ouyang is an associate professor at the University of Nevada, Reno. She is an integrative physiologist interested in how animals adapt to urban environments, including those living in pervasive light pollution.

Reading Mathematics

Brian Hayes

ONCE UPON A PRIME: The Wondrous Connections Between Mathematics and Literature. Sarah Hart. 304 pp. Flatiron Books, 2023. $29.99.

The Commonwealth of Mathematics and the Republic of Letters share a long, unguarded border. Conventional wisdom says there's no need to fortify the boundary line, because so few citizens of either realm have any inclination to cross it. It's not that math types and literary types are enemies; perhaps they are merely indifferent to each other's ideas.

In *Once Upon A Prime*, Sarah Hart reveals that there is more cross-border traffic than most of us realize. Various kinds of mathematical contraband have been smuggled into the works of poets and novelists, and at least a few mathematicians have dabbled in works of imaginative literature. Hart wants to encourage such cultural commerce, and perhaps even establish more formal diplomatic relations.

Once Upon A Prime offers a three-part catalog of literary works that borrow from the world of mathematics in one way or another. In Part I, mathematical ideas supply patterns and structures that give shape to poetry or to works of prose fiction. An example is the Japanese art of *haiku*, poems with 17 syllables arranged in three lines of five, seven, and five. Hart points out that 3, 5, 7, and 17 are all prime numbers, divisible only by 1 and themselves. The Japanese *tanka* form has five lines with syllable counts of five, seven, five, seven, and seven; the total is 31, which is another prime. This prevalence of primes is intriguing, although Hart offers only tentative speculations about its effect on the aesthetics of the poems.

The rhyme schemes of poems also have a mathematical structure. A rhyme scheme can be represented by a sequence such as *ABAB* or *ABBA*, where matching letters indicate lines with the same end rhyme. A natural question for those with a mathematical bent is how many rhyme schemes are possible for verses with a given number of lines. The answer is a sequence of numbers beginning 1, 2, 5, 15, 52, 203. . . . That is, a one-line poem has just one possible rhyme scheme, *A*. With two lines the alternatives are *AA* and *AB*. Three-line verses have these five possible schemes: *AAA*, *AAB*, *ABA*, *ABB*, *ABC*. The elements of the sequence grow rapidly for longer verses; with 10 lines, there are 115,975 possibilities.

Hart explains that the numbers counting rhyme schemes are known as Bell numbers, after the mathematician Eric Temple Bell. To my disappointment, however, she does not explain in any detail why this particular sequence is associated with the rhyme schemes, or how to calculate the Bell numbers.

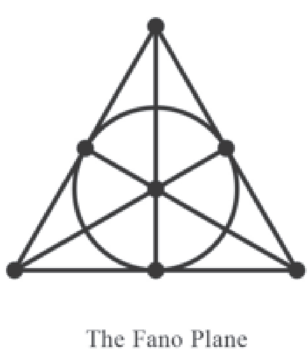
The celebration of mathematically inspired literary structure reaches its zany zenith in the works of Oulipo, a group formed in 1960 by the French writers Raymond Queneau and François Le Lionnais. "Oulipo" is an abbreviation of *Ouvroir de littérature potentielle*, usually translated as Workshop of Potential Literature. A characteristic work from the group is Queneau's *One Hundred Thousand Billion Poems*, published as a book of 10 pages. Each page is slit horizontally to form 14 strips, and each strip bears a single line of text. Selecting one of the 10 strips in each of the 14 positions generates the promised 10^{14} poems. They are all sonnets conforming to the same rhyme scheme. American mathematics writer Martin Gardner claimed they all make sense, although he can't possibly have read them all.

Hart herself bravely enters the potential-literature game with a device she calls Fano fiction. The Fano plane, named for the Italian mathematician Gino Fano, is a geometric construction with seven points and seven lines, arranged as shown below. Each point lies on three lines, and each line touches three points. (One of the lines is drawn as a circle; no arrangement of the points allows all seven lines to be drawn as straight segments.) By associating a word with each point, Hart generates a story made up of seven three-word sentences, beginning "Book top act! Best book fast!" The story consists of 21 words, but explaining what they mean would take at least four times as many.

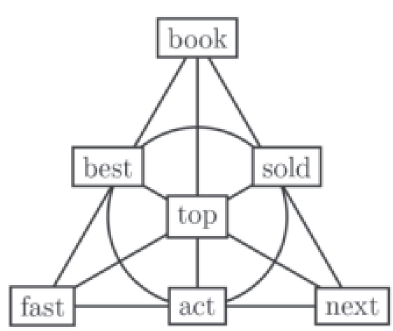
Part II of *Once Upon A Prime* explores mathematical ideas that enter literary works as metaphors or other figures of speech. Hart describes her experience of reading Herman Melville's *Moby-Dick* for the first time:

> As I read on, I kept encountering mathematical allusions, so many in fact that it became clear to me that Melville obviously relished mathematical ideas—they were bound to escape from his mind onto the page, and when he reached for a metaphor, more often than not something mathematical would present itself.

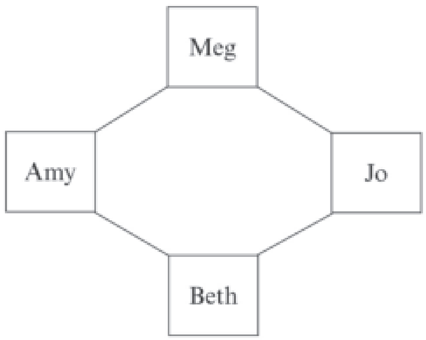
The premier example is Melville's description of iron cauldrons called try-pots aboard the whaling ship *Pequod*. These large cooking vessels, where whale blubber was rendered into oil, have a cross section that the narrator, Ishmael, identifies as an inverted cycloid. The cycloid is the curve traced by a point on the perimeter of a disk



The Fano Plane



The Fano plane (*left*) consists of seven points joined by seven lines. Sarah Hart turns it into a storytelling device by associating a word with a point. From *Once Upon A Prime*.



Visits reported by the four sisters of *Little Women* are recorded in a structure called an *interval graph*, where two sisters are connected by a line if their visits overlapped. But the sisters' reports cannot all be correct, because the interval graph must have a chord connecting Meg and Beth or Amy and Jo. From *Once Upon A Prime*.

as the disk rolls on a plane. Ishmael, having climbed into one of the pots to scrub and polish its interior, muses on the geometry of the surface: "It was in the left hand try-pot of the *Pequod*, with the soapstone diligently circling around me, that I was first indirectly struck by the remarkable fact, that in geometry all bodies gliding along the cycloid, my soapstone for example, will descend from any point in precisely the same time."

The cycloid curve was a hot topic among mathematicians in the 17th century, when Christiaan Huygens proved the "remarkable fact" noted by Ishmael: The inverted curve is a *tautochrone* (a term that might be translated "same time"). A body sliding along the curve without friction will reach the bottom in the same amount of time, no matter where along the curve it is released. It's surprising that Ishmael, a sailor with little formal education, would be acquainted with such a geometric oddity, but then Ishmael is quite the know-it-all, discoursing on everything from ancient history to zoology.

A more pointed question is how Melville came to know of the cycloid and the tautochrone. Hart has an answer to propose: He learned it from Joseph Henry, one of the preeminent American scientists of the 19th century. Henry's first teaching appointment was at the Albany Academy, a school for boys where young Melville was a star pupil. This aspect of Melville's biography was brought to light in a 2016 doctoral thesis by Meredith Farmer, who argues that Melville's interest in the sciences was not merely ignored, but had been actively suppressed by some biographers.

Part III discusses works in which mathematics (and in some cases, mathematicians) become central, thematic elements of the story. For example, fractals and chaos theory, both trendy mathematical topics in the late 20th century, were important plot devices in Michael Crichton's novel *Jurassic Park*. Cryptography was a theme in works by Edgar Allan Poe, Jules Verne, and O. Henry. We visit Professor James Moriarty, the archvillain of the Sherlock Holmes stories, whose professorship is in mathematics. Hart points out that Holmes himself, with his skills in logical deduction, might have been given mathematical credentials, but Arthur Conan Doyle thought the public would have trouble warming up to such a figure. Better an opium addict than a mathematician.

The longest section of Part III delves into Edwin A. Abbott's 1884 book *Flatland: A Romance of Many Dimensions*. This is a work with a highly mathematical premise: Various creatures inhabiting a two-dimensional universe try to imagine life in three dimensions, thereby challenging us denizens of 3D to conceive of a fourth dimension. There's no disputing that mathematical ideas take center stage in this tale. Indeed, it's really more of a math book than a novel, and library catalogs treat it as such, putting *Flatland* on the mathematics shelves, not with the fiction.

For me, the most engaging section of Part III deals with Hart's attempt to resolve a seeming paradox in a Jorge Luis Borges short story, "The Library of Babel." The library holds a single copy of every possible book of a certain length; each volume consists of 410 pages, holding 1,312,000 characters drawn from an alphabet of 25 letters and punctuation marks. Thus, the library's total inventory is $25^{1,312,000}$ books, which is an immense number, but still finite. The paradox is that the library itself is said to go on forever, with every shelf filled. You can walk left or right in any corridor and never come to the end, and likewise, you can go up or down stairways from floor to floor without reaching the top or the bottom. How can we reconcile this boundless space with a finite collection of volumes? Hart proposes that we map the corridors and stairways onto the surface of a *torus*, or doughnut. That way, you can wander forever without coming to the edge of the world.

By education and profession, Hart is a member of the mathematical community, rather than the literary one. She is a professor of mathematics at Birkbeck College in London and is also the current Gresham Professor of Geometry, a post that calls for delivering a series of lectures for the general public. She is a talented and enthusiastic expositor, who clearly takes great pleasure in turning people on to the charms of mathematics. It's a little perplexing, then, that in this book she sometimes shies away from fully explaining the mathematical ideas she discusses.

As mentioned, the Bell numbers and rhyme schemes receive only cursory treatment. Another example comes up in connection with a structure called an *interval graph*. Hart introduces the idea with a story about the four sisters of *Little Women* visiting their Aunt March. The interval graph records these visits by drawing a line between two sisters if their visits overlapped. Reports from Meg, Jo, Beth, and Amy lead to the interval graph shown at upper left. Hart then writes:

> This graph has a cycle Meg—Jo—Beth—Amy. But there is a theorem in graph theory that says that every interval graph is 'chordal.' What this means is that somewhere in every cycle there has to be a chord—an intermediate line joining two of its points. If a graph doesn't have that property, then it can't be a true interval graph. Here, it means there must be a line either joining Meg to Beth, or one joining Amy to Jo.

I was fascinated by this observation, but also frustrated that Hart gave no hint of why the theorem is true. Perhaps she chose not to spell out the details for fear of scaring away math-shy readers. Hart writes, "That feeling we get when we read a great novel or a perfect sonnet—that here is a beautiful thing, with all the component parts fitting together perfectly in a harmonious whole—is the same feeling a mathematician experiences when reading a beautiful proof." Agreed! And the reader should not be denied a taste of the delights to be found in reading proofs and other kinds of mathematical literature.

Brian Hayes is a former editor and columnist for American Scientist. *His most recent book is* Foolproof, and Other Mathematical Meditations *(MIT Press, 2017).*

Sigma Xi Today

A NEWSLETTER OF SIGMA XI, THE SCIENTIFIC RESEARCH HONOR SOCIETY

A Girl Is Born to Be a Scientist

The following is an excerpt from a blog post by Sigma Xi President-elect Dr. Marija Strojnik.

When I was a young physics student, there were very few other women studying STEM disciplines. I lacked female role models due to the societal standards of the time. There were no female professors in the technical departments at any of the universities that I attended. I felt isolated in classes where the teachers spoke only among men. It took me additional psychological effort to get closer to classmates who were uncertain of my abilities, especially when carrying out laboratory assignments or group projects. Fortunately, I found eventual success working in group environments, but the initial integration was always difficult.

Today, I feel happy in my work as a scientist. I encounter new and interesting research challenges every day. I feel comfortable in confirming that I was born to be a scientist. I invite all girls and women with interests in science, engineering, or technology to pursue projects in those fields. Unfortunately, many girls and women have learned to avoid this experience. However, I think that a girl can always read books on her own and sign up for school or community projects for extracurricular and complementary education.

Read the full article at **sigmaxi.org/strojnik**

Sigma Xi Today is managed by **Jason Papagan** and designed by **Chao Hui Tu.**

From the President

Building the Future of Research: Equity, Internationality, and the Younger Generation

I am delighted once again to greet our Sigma Xi members. This is the last column I will write in my capacity as president of Sigma Xi. By the time it is published, I will be nearing the end of my presidency, and Dr. Marija Strojnik will be taking over. I note with pleasure that a Greek will be passing the baton to a Slovenian. This small observation shows the internationality of our Society. We are home to thousands of scientists from around the world, scientists who care about what they do, how they do it, their professionalism, and their dedication to achieve something good for this world, for its citizens, and for all our patients.

This past year, the Society has addressed a number of important concerns affecting science. We were reminded once again how crucial it is that our data are collected carefully and accurately, as well as being properly disseminated throughout the world in a way that can be clearly understood. We must both understand our scientific results and prevent the misinterpretation of those results, which has become a major problem in our society. In the end, if we are not able to communicate what our findings truly mean, then we are just as responsible as those who would misuse them.

Another major challenge in modern science is reaching the younger generation. My recent trips to Vanderbilt University and the University of Texas at San Antonio showed me yet again that the younger generation is hungry to learn, to ask questions, and to understand how to contribute and respond to societal needs. I saw the same thing internationally in my recent trips to Romania and Portugal. Thinking ahead to the future, I am always trying to identify new ways to attract younger scientists to Sigma Xi.

I became a member of Sigma Xi exactly 50 years ago this month, as a graduate student at MIT. It was a great honor to be elected then, and I still believe it is a great honor today. Last November, I saw that same pride in the eyes of our new inductees (and their parents) at the Society's induction ceremony in Alexandria, Virginia.

So, my final message is a simple one: Let's reach out to more young scientists, let's make them active members of Sigma Xi, and let's keep building the scientific infrastructure of our world.

Nicholas A. Peppas, ScD

FACES of GIAR : Peter Roopnarine

Grant: $500 in Fall 1990
Education level at time of the grant: PhD student

Project Description: I used my Grants in Aid of Research (GIAR) award to support a second paleontological field season, traveling to southern California and Baja California. The goal was to visit a number of marine fossil localities in San Diego and northern Baja, on both the Pacific and Gulf of California coasts.

My project examined changes to the marine faunas of tropical America during the past 35 million years, focusing on changes associated with the closure of the Panama Seaway approximately three million years ago, which separated the Caribbean and Pacific portions of tropical American waters. Changes associated with seaway closure were profound, including an important contribution to the onset of Northern Hemisphere glaciation, marine extinctions on the Caribbean side, and the onset of upwelling and high productivity on the Pacific side. Documenting the evolutionary and ecological consequences of those changes involves extensive collecting and knowledge of the fossil faunas from that broad geographic area. My Sigma Xi grant allowed me to visit and examine important fossil localities on the Pacific side of the seaway.

How did the grant process or the project itself influence you as a scientist/researcher? It was incredibly important to get this grant, as it was the first grant that I applied for as a doctoral student, and it allowed me to start my fieldwork. I've gone on to do many years of fieldwork in Baja California, and that experience, in which I lead a group of five, gave me the confidence both to conduct field research, and to be an expedition organizer and leader.

Where are you now? I am now the curator of geology and paleontology at the California Academy of Sciences in San Francisco.

Sigma Xi Launches New STEM Career Workshop

The inaugural Sigma Xience workshop took place March 21–24. The virtual event connected students and early-career STEM professionals with award-winning scientists, leaders, and industry professionals during a series of panel discussions and workshops.

The immersive, four-day event included mentoring from private industry, academia, nonprofit, and engagement professionals. Sigma Xi leaders were joined by featured panelists including MIT's Jeffrey Toney, PhD Balance's Susanna Harris, the University of Michigan's Lola Eniola-Adefeso, and North Carolina Central University's Antonio Baines and Julie Horvath.

Participants took part in discussions and activities with the goal of creating personalized STEM career toolkits to carry into the launch and nurturing of their present and future careers. Topics included:

- How to choose advisors
- How science is funded
- Strategies to broaden the impact of your research
- Managing stress
- Creative applications of science to social justice and human rights issues
- The art of communicating research and getting published
- What can I do with a PhD in science?

Learn more information about Sigma Xience 2023 and potential future events by visiting **sigmaxi.org/SigmaXience**.

2023 Women in STEM

Every March, Sigma Xi celebrates Women's History Month by showcasing a group of women in STEM at various points in their careers. Kathy Lu, Anne Savage, Tashara Leak, and Olivia Lanier highlight this year's profiles. Read the full interviews from these and other 2023 Women in STEM at **sigmaxi.org/WHM23**.

Kathy Lu, PhD

What is your current role?

I am currently a full professor in materials science and engineering at Virginia Tech. I am also the incoming president-elect of Sigma Xi, beginning in July 2023. My research interest is related to polymer-derived ceramics and composites, materials degradation in harsh environments, data-driven materials processing and characterization, materials synthesis, and fundamental studies.

How can men be better allies for #WomenInSTEM and gender equality?

As the majority in the STEM field, men can be good mentors and supporters of women by offering mindfulness, guidance, and growth opportunities. This will help to create a more supportive and inclusive environment for all. Men should also listen to and learn from the experiences and perspectives of women. This means taking the time to understand the challenges and barriers that women face and being open to feedback and criticism. Men can use their influence to amplify the voices of women in STEM, for example, by promoting their work, giving them credit for their ideas, and advocating for their inclusion in important discussions and decision-making processes.

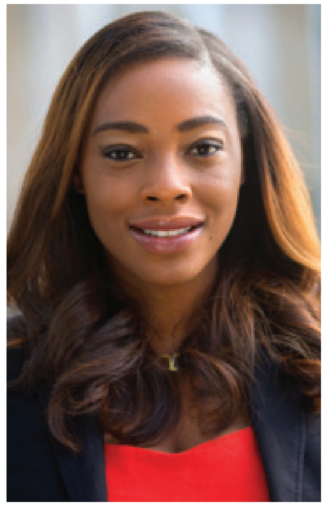
Olivia Lanier, PhD

What is your current role?

I am a provost early career postdoctoral fellow at the University of Texas at Austin. I work on developing oral delivery platforms for patients with autoimmune diseases as a more accessible alternative to infusion-based therapies.

What is it like to be a woman in STEM? Do you feel that your gender gives you a different perspective from your male counterparts?

My gender, along with many other personal attributes and personal experiences, has provided me with a different perspective than others. Everyone has a unique set of life experiences that contributes to their passions and interests, as well as their blind spots. Only by improving diversity and inclusion in STEM will we be able to create technologies that work for all people and eliminate blind spots in design. In fact, studies have shown that a person's identity contributes to their research interests. For example, as more women entered the STEM field, more research on women's health emerged.



Tashara Leak, PhD, RD

What is your current role?

I am an assistant professor in the Division of Nutrition Sciences at Cornell University and in the Division of General Internal Medicine at Weill Cornell Medicine. I am also a cofounder of the Cornell Action Research Collaborative, an initiative that fosters infrastructure for researchers, community organizations, and policy makers to collaborate on pressing societal issues (e.g., food insecurity, health inequities).

What is one career accomplishment you would love to achieve?

I would love to grow in academic leadership. We are still in an era of firsts; you still don't see many women in academic leadership. There are system-level changes that I want to make as a scientist, and I have a unique lens both as a woman and as a Black American. Having a seat at the table would allow me to make more institutional-level changes.

Anne Savage, PhD

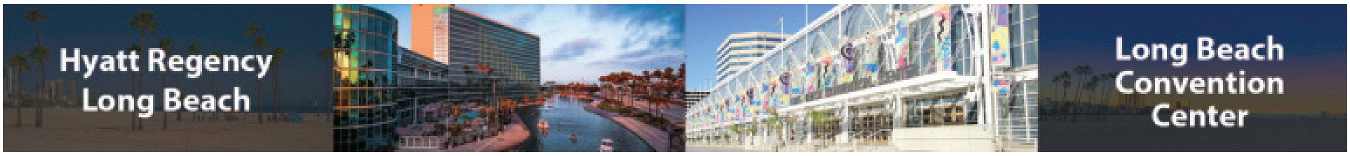
What is your current role?

I've retired as the conservation director for Walt Disney Parks and Resorts, but I remain active as the founder and executive director for Proyecto Tití, Inc., a conservation organization involved in the study and protection of the critically endangered cotton-top tamarin in the tropical forests of Colombia.

What advice do you have for other women considering or starting a career in STEM?

One of the most important things to remember is that you don't need to excel at everything you do, but you need to know who is the best in class to help you when you find yourself entering areas that are outside of your comfort zone as you grow in your career. It is very common that you learn the basics of your field while you are in school, but when you enter the workforce you may need to apply those learnings in different scenarios. A strong network of friends and colleagues in your field and related to your field is always great to call on when you need a little extra advice.

Visions for Ethical Research to Highlight IFoRE '23



RESEARCH

Scientists, engineers, research and technology professionals, government and academic administrators, postdocs, graduate students, undergraduate students, and high school students are all invited to submit abstracts and workshop descriptions for IFoRE '23. Submissions should address how your work contributes to a healthy and prosperous future, based on research, analysis, model building, verification, evaluation, and policy. Using tools for examining the natural world—from optical sciences and vision systems to sociological and environmental sciences—scientific objectivity and ethics must be clear to all stakeholders in society. We encourage focusing on interdisciplinarity and humanism consistent with knowledge acquisition in the 21st century.

IFoRE '23

POWERED BY SIGMA XI

November 10–12, 2023

Long Beach, California

POSSIBLE SYMPOSIA TOPICS

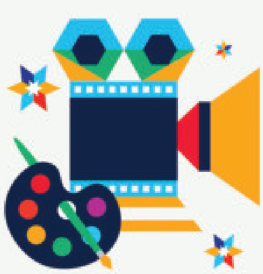
Gather your colleagues to submit a symposium idea. Possible topics include: Chemistry, biochemistry, biology, and pharmaceutical sciences; Vaccines; Treating and curing rare diseases; Artificial intelligence for human well-being; Combating misinformation; Biosoma; Phenomenon of being human; Ethics in health administration; Imaging in (cryo-) electron microscopy; Ecology and evolutionary biology; Glass as a wonder material; Novel materials, from nano- to meta-, from 1D through 3D; Imaging for knowledge while imagining a more ethical world; Interdisciplinarity of human endeavors; and Improving graduate education programs.

CAREER TUTORIALS

Bring your students to develop their research skills and gain professional development training. The Southern California chapter of Sigma Xi and others are organizing a series of career tutorial sessions to orient and empower young and future scientists and engineers to function in an ever more demanding work and life environment, while maintaining their allegiance to the core values of excellence, integrity, and companionship.

TRACKS

Tracks will cover the following: Excellence in research to include ethics, open science, and interdisciplinarity; Research impacts to emphasize science communication and engagement with citizenry and politicians, to guide science policy, civic science, and entrepreneurship; and Excellence in STEM education to achieve social mobility and the establishment of a thinking polis, starting with K–12 education. Student research at the high school, undergraduate, and graduate levels will also be featured throughout the conference. Visit **experienceIFoRE.org** to learn more.



STEM ART AND FILM FESTIVAL

We invite creatives using the visual arts, data visualizations, scientific photography, and more to compete in this year's festival, which focuses on visualizing the natural world. Science, technology, engineering, and mathematics are understood using human vision, as well as machine instruments as extensions of human perception. Submit your artwork, images, film, video, or photos to wow the world and compete for prizes.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INTERNATIONAL FORUM ON RESEARCH EXCELLENCE
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experienceIFoRE.org
Sigma Xi Annual Meeting
is now
IFoRE